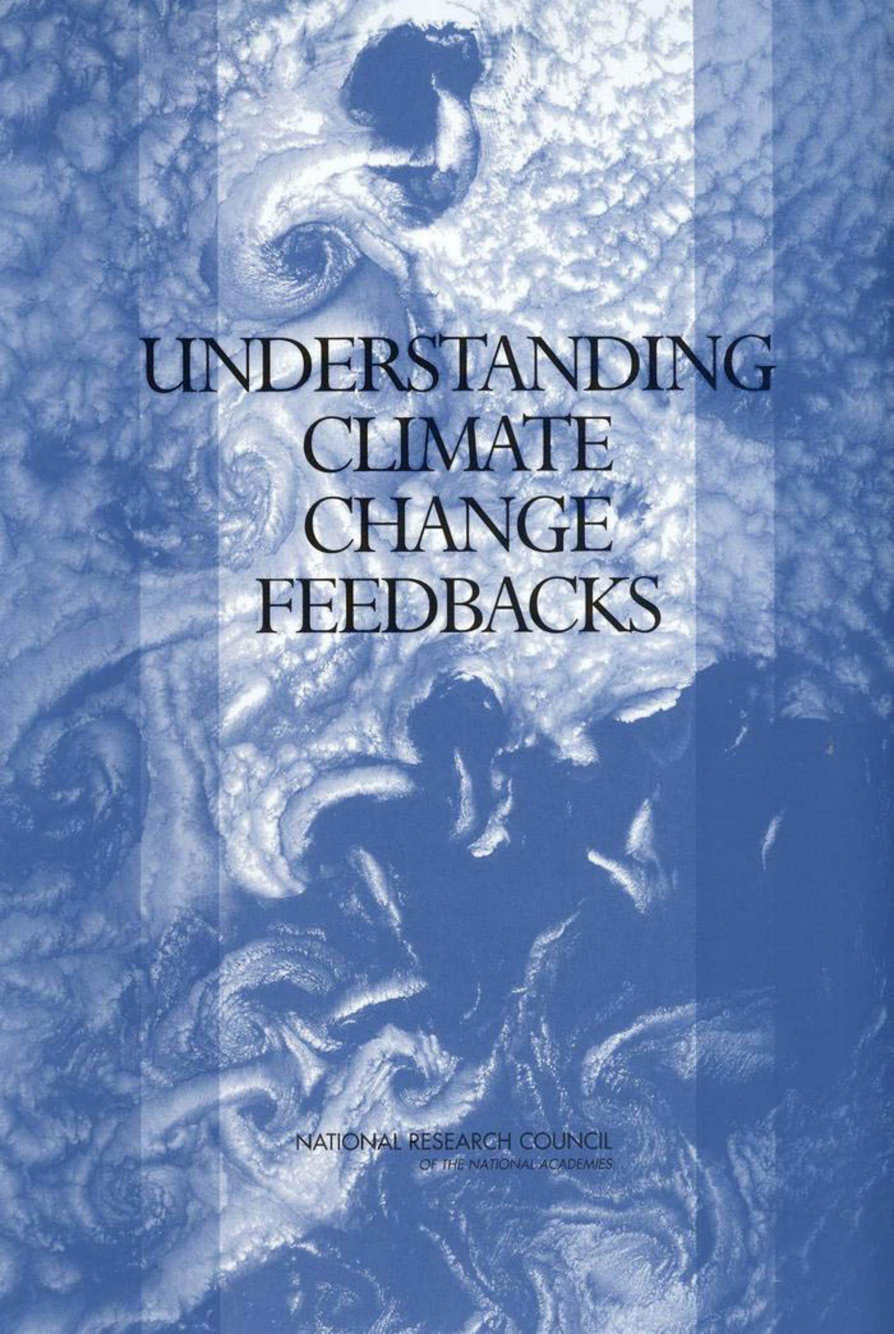

UNDERSTANDING CLIMATE CHANGE FEEDBACKS

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UNDERSTANDING CLIMATE CHANGE FEEDBACKS

PANEL ON CLIMATE CHANGE FEEDBACKS
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Cover: A vortex street near the Canary Islands. A vortex street often occurs when cloud formations over the ocean are disturbed by wind passing over land or another obstacle. In this Moderate Resolution Imaging Spectroradiometer (MODIS) image from July 5, 2002, marine stratocumulus clouds have arranged themselves in rows, or streets, which are usually parallel to the direction of wind flow. Downwind of obstacles, in this case, the Canary Islands off the west African coast, eddies create turbulent patterns called vortex streets. Marine boundary layer clouds have a large effect on Earth's energy balance and understanding them is important to predicting the response of climate to human activities.

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PREFACE

The National Research Council (NRC), the operating arm of the National Academies, has over the years produced an extensive body of work focused on issues relevant to observing and understanding changes in climate. Several NRC reports have provided advice to guide the evolution of U.S. research priorities[1] and, most recently, the Climate Change Science report (NRC, 2001a) concluded that

> [m]aintaining a vigorous, ongoing program of basic research, funded and managed independently of the climate assessment activity, will be crucial for narrowing these uncertainties. . . . The ability of the United States to assess future climate change is severely limited by the lack of a climate observing system, by inadequate computational resources, and by the general inability of government to focus resources on climate problems. Efforts are needed to ensure that U.S. efforts in climate research are supported and managed to ensure innovation, effectiveness, and efficiency.

Although these statements are addressed toward the entirety of the climate research enterprise, the report also specifically discussed the importance of reducing the uncertainties associated with climate change feedbacks such as water vapor, clouds, and snow cover. This report is an attempt to look in detail at that challenge and identify ways to improve our understanding of climate change feedback processes.

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[1] *Decade-to-Century-Scale Climate Variability and Change: A Science Strategy* (NRC, 1998a); *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998b); *Adequacy of Climate Observing Systems* (NRC, 1999a); *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1999b); *Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001b); *The Science of Regional and Global Change: Putting Knowledge to Work* (NRC, 2001c).

Over the past decade we have learned much about the complex natural processes that influence climate variability and change, and our ability to model climate has increased significantly. In addition, we have gained a better appreciation for the important connections between physical, biological, and social sciences in the climate system. We have also begun to better identify those parts of the climate system that are particularly important and not well understood, and therefore limit our ability to project the future evolution of Earth's climate. One of these critical areas is our understanding of the role of feedbacks in the climate system and their role in determining climate sensitivity. The ultimate goal of climate feedbacks research is to enable accurate predictions of the response of Earth's climate to specified natural or human-induced influences on the climate system.

Clearly, humans play a major role in some feedback loops, particularly those involving biological and land surface processes, and it can be difficult to distinguish between the effects of human activities and natural processes. To maintain a sharp focus for this study, however, we have not addressed those feedbacks that depend on a human response to either amplify or damp an initial perturbation. We recognize, however, that research into climate change must ultimately embrace natural and human-induced feedbacks holistically. Furthermore, we do not address uncertainties associated with natural or human-induced climate forcing. The question addressed here is, "If humans provide specified inputs to atmospheric composition or changes in land surface that force changes in the climate system, how do natural climate processes influence our ability to project the response of climate to that forcing?"

Although this report focuses in particular on climate change feedbacks, this research cannot be separated from other efforts to understand the climate system. Many of the research approaches and techniques used to better understand climate feedbacks will also shed light on other aspects of the climate system. Moreover, climate feedbacks research will take place in the context of continuing efforts to detect climate change, attribute climate change to specific causes, and make practical projections of future climates. For these reasons we have taken a broad view of what constitutes a feedback process, including in our definition not only the processes that affect the equilibrium response of global mean surface temperature to a specified forcing but also natural processes whereby climate changes feed back on the rate of warming, the magnitude of the climate forcing, or the spatial pattern of climate change.

The Panel on Climate Change Feedbacks interpreted its charge (see Executive Summary) as a request for broad guidance on the key avenues of research to be pursued to better understand climate feedbacks and their role in climate sensitivity. Given our resources, we did not attempt to formulate a detailed research strategy, which would take significantly more time and community input than our process allowed. Rather, we sought to review the science of climate feedback processes broadly and call attention to those areas where additional focus might bear fruit in the near term. Thus, this report should be viewed as a starting point for the formulation of a long-term research strategy for addressing the issue of climate feedback processes and their role in climate sensitivity. Comprehensive disciplinary plans have in some cases already been carried out by groups of scientists convened by the agencies. Where this work is relevant to the report's discussion we have referred to it.

The Panel's deliberations included some critical and difficult issues that did not make it into the final report. These include the scientific definition of uncertainty, its quantitative evaluation, and its relation to the development of policy options regarding climate change. I, like many scientists, believe that directed, high-quality research will increase understanding, and thus reduce uncertainty that is associated with incomplete knowledge of the climate system. My belief is that this improved knowledge can then be used to support decision making for the benefit of society, although this view is not universally accepted. In my view the proper and useful role of scientists is to use the scientific method to seek after natural truth as best we can. This being said, it is difficult to argue in a quantitative way that increased understanding will lead quickly to narrowing of the range of estimates of how much global warming will result from a doubling of atmospheric carbon dioxide. Indeed, new discoveries may widen the apparent possibilities. In this report we focus our attention on the key research questions necessary to better understand the feedback processes that we believe to be the most important. Larger questions are left to other groups to address.

The primary funding for this study was provided by the U.S. Global Change Research Program, with additional funds from the National Science Foundation. Representatives from NSF and other relevant agencies, including the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the Department of Energy provided encouragement and input to the study, in particular through a meeting with the Panel in February 2002.

In closing, I wish to thank the members of the Panel on Climate Change Feedbacks for their efforts in preparing this report. I also thank all those who participated in the Panel's information-gathering workshop in Boulder, Colorado, during August 2001 and in the Panel's meeting with federal agencies during February 2002 in Washington, D.C. Peter A. Schultz did an excellent job as study director and contributed greatly to this report. Chris Elfring made major contributions during the review and revision process.

Dennis Hartmann
Chair

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Tom Wigley, National Center for Atmospheric Research, Boulder, Colorado
James Anderson, Harvard University, Cambridge, Massachusetts

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Richard Goody, Harvard University, and Kuo-Nan Liou, University of California, Los Angeles. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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EXECUTIVE SUMMARY

The climate of Earth is evolving, and understanding this change can help us to be prepared to deal with the consequences for water resources, agriculture, energy demand and supply, health, recreation, and ecosystems (IPCC, 2001b). Climate changes can be initiated by external factors forcing the climate system. These climate forcings include natural factors such as changes in energy flux from the Sun, variations in the Earth's orbit, and volcanic eruptions, as well as human activities, such as production of greenhouse gases and aerosols and modification of the land surface. Over the next century it is likely that forcing of the climate system by human activities will greatly exceed changes in forcing caused by natural events.

Processes in the climate system that can either amplify or damp the system's response to changed forcings are known as feedbacks. According to estimates generated by current climate models, more than half of the warming expected in response to human activities will arise from feedback mechanisms internal to the climate system, and less than half will be a direct response to external factors that directly force changes in the climate system (NRC, 2001a). Moreover, a substantial part of the uncertainty in projections of future climates is attributed to inadequate understanding of feedback processes internal to the natural climate system (IPCC, 2001a). Therefore, it is of central importance to understand, model, and monitor climate feedback processes.

At the request of the interagency U.S. Global Change Research Program, the Panel on Climate Change Feedbacks of the Climate Research Committee was given the following tasks:

1. Characterize the uncertainty associated with climate change feedbacks that are important for projecting the evolution of Earth's climate over the next 100 years, and
2. Define a research strategy to reduce the uncertainty associated with these feedbacks, particularly for those feedbacks that are likely to be

important and for which there appears to be significant potential for scientific progress.

The study looks at what is known and not known about climate change feedbacks and seeks to identify the climate feedback processes most in need of improved understanding. This report suggests an approach by which progress toward better understanding of climate feedback processes can be measured and accelerated. Such improvements will serve policy makers as they deliberate on climate-related decisions.

THE NEED FOR CLIMATE FEEDBACKS RESEARCH

In recent years the principal way scientists have sought to understand changes in climate has been to simulate the record of global mean surface temperature over the period of the instrumental temperature record from about 1860 to the present (e.g., Hansen et al., 1981; IPCC, 2001a). Such comparisons allow testing of our understanding of climate forcing, climate sensitivity, and heat storage in an integrated global sense, but they are imperfect. A second approach has been to make model-to-model comparisons of climate simulations, and this has revealed significant differences and similarities between models (Gates et al., 1998; Covey et al., in press). At this point in time this Panel believes that an effort to refine our understanding of the key climate feedback processes and improve their treatment in models used to project future climate scenarios is an effective way forward in the quest to better understand how climate may evolve in the future in response to natural and human-induced forcings. An appropriate strategy for accomplishing this is to make more vigorous comparisons of models with data and to focus particularly on observational tests of how well models simulate key feedback processes. A key finding of this report is that **an enhanced research effort is needed to better observe, understand, and model key climate feedback processes.**

Key Observations Needed to Monitor and Understand Climate Feedbacks

Previous reports by the National Research Council (NRC) have emphasized the need for stable, accurate, long-term measurements of climate variables (NRC, 1999a). Because of their important role in determining the magnitude of climate change, additional variables must be monitored to assess the role of feedback processes in climate change. Observation of feedback processes is needed to better understand these processes, to identify the causes contributing to observed climate changes as they occur, and to test and improve simulations of climate. As described in the body of the report, some variables key to feedback processes are not being adequately monitored on a long-term basis. To understand and monitor climate feedback processes requires good observations of the basic state of the climate system, plus some additional variables that monitor specific feedback processes.

> *Recommendation:*
> *An integrated global climate monitoring system must include observation of key climate feedback processes. Stable, accurate, long-term measurements should be made of the variables that characterize climate feedback processes.*

To better understand and model climate feedback processes and to interpret the role of feedbacks in climate changes that may develop in the future, research efforts must monitor not only traditional climate variables like temperature and precipitation but also variables that define the feedback processes. Key long-term measurements that are needed to monitor and understand climate change feedbacks are:

- temperature, humidity, precipitation, and wind;
- radiation budget at the top of the atmosphere and at the surface;
- global cloud and aerosol distributions and properties;
- temperature and salinity of the upper ocean and of other portions of the ocean that affect interannual to decadal climate change;
- terrestrial vegetation, soil moisture, snow extent and its properties, and sea-ice distribution and thickness; and
- atmospheric CO_2, O_3, O_2-N_2 ratio, and ocean color.

Several of these variables are being monitored for purposes of weather analysis and prediction, but none adequately for climate purposes.

As recommended in several previous NRC reports there are advantages to collecting these observations in the context of an integrated global climate monitoring system (e.g., NRC, 1999a). Such a system is required for other aspects of climate change research and applications not addressed in this report, including for climate change attribution and detection, and for providing a broad range of climate services (NRC, 2001e). The collection and validation of all these datasets will require international collaboration and cooperation among U.S. agencies.

In addition to using the observations as climate data records (see NRC, 1999a and 2000b, for a description of the characteristics of climate data records), they should also be incorporated in 4-D data assimilation. Subject to important caveats, the resulting integrated datasets will be suitable for model initialization, model validation, and for multivariate diagnostic studies on climate time scales.

Evaluating Progress in Understanding Climate Feedbacks

To ensure focused research and to measure progress, we need observable climate metrics that define the feedbacks sufficiently both to understand the key processes and to test and improve the simulation of these processes in climate models. A climate feedback is a set of numbers that can be derived from both observations and model output, and that characterizes the nature of a climate feedback process. It is important that this characterization be useful for better understanding the feedback process and for assessing the accuracy of its simulation in climate models. Metrics can use observed past climate trends, but should also use the variability of climate on other time scales that are better observed and where forcing is larger, such as seasonal and diurnal time scales. Good metrics must be focused on objectives that will increase confidence in our ability to usefully model climate feedback processes, and must be defined in terms of variables that are well observed. They should evolve as our understanding and observations improve.

> *Recommendation:*
> *Both global and regional metrics that focus on feedback processes responsible for climate sensitivity should be used to more rigorously test understanding of feedback processes and their simulation in climate models.*

A good set of diagnostic tests for climate feedback processes should capture the covariation or coupling between the system's components. If effectively employed, these metrics can be an essential tool to help organize and stratify diagnostic analyses, as well as to relate model simulations to the fundamental aspects of observed phenomena. Successful reproduction of these observed metrics by climate models will not guarantee that climate models will give reliable projections of future climates, but testing climate models against a large set of carefully considered metrics is an effective way forward. They can also be a useful tool for observing the evolution of the climate system and thus make important contributions to the field of climate change detection and attribution. The set of metrics will evolve with time as understanding and simulation of the climate system evolve and improve.

A few examples of possible climate feedback metrics can be given. At the global or regional scale, the covariability of sea-surface temperature, clouds, upper-tropospheric water vapor, the vertical profile of atmospheric temperature, and other observations can be studied over a variety of time scales, including well-observed natural scales of variability, such as the diurnal, annual, and El Niño Southern Oscillation (ENSO) signals. These covariance metrics should then be applied to model simulations to pinpoint those aspects of the models that appear to represent nature accurately and those that require further work. A metric that might enable improvement of feedback processes over land would be observed diurnal and seasonal variations of temperature, clouds, precipitation, and soil moisture. Many other possible regional metrics for testing the simulation of climate system feedbacks can be envisioned, and some are discussed further in Chapters 2 through 8.

A step toward developing widely accepted metrics to evaluate feedback processes could be for the relevant agencies to organize a workshop or series of workshops to define a set of observational and diagnostic metrics that can be used to test understanding and modeling of climate feedback processes. These workshops could include scientists engaged in observation, diagnosis, and modeling of climate and climate processes.

Climate Modeling and Analysis for Climate Feedbacks Research

To test understanding and modeling of climate feedback processes using a set of climate feedback metrics requires a substantial infrastructure and a proportionate intellectual effort. To undertake a rigorous program of testing the simulation of climate feedback processes in our most capable climate models requires that the observations and the expertise in applying them be brought together with the modeling capability. Previous NRC reports have stated the need for capable and effective climate modeling facilities (NRC 1998a, 2001c), and have recommended the development of centralized operations for climate predictions and ozone assessments (NRC, 2001c). To advance understanding of climate change feedbacks and their role in climate sensitivity it is essential that U.S. climate modeling facilities also have the capability and mandate to test climate feedback processes and their interactions using the most discriminating observational constraints. Within the context of climate feedback processes, this will also address the need for uniform criteria with which to judge climate models (NRC, 2001c).

> *Recommendation:*
> *Climate modeling facilities in the United States must be given the capability and mandate to test understanding and simulation of climate feedback processes and their interactions using the best observational constraints on climate feedback processes. Periodic assessment of the progress being made by major climate models should be conducted to evaluate the ability of these models to simulate the processes underlying key climate system feedbacks.*

One interdisciplinary coordination challenge is to lessen the separation between U.S. observational and modeling research (NRC, 2001c). Representation of processes related to climate feedbacks in global climate models is a complex and challenging undertaking, which often proceeds without adequate connection to the developing observational basis. It is also difficult for the observational community, which tends to focus on the technical aspects of data collection and analysis, to find the time and resources to assist in the development of Earth system models. While observations are used to test the climatological statistics derived from climate simulations, more attention needs to be given to using data to rigorously test the simulation of feedback processes in these models and their role in determining climate sensitivity.

Another opportunity to encourage progress in climate feedbacks research is to reduce the separation between operational numerical weather prediction centers and climate research centers in the United States. Many climate feedback processes operate on time scales short enough to be tested effectively by comparing numerical weather forecasts with instantaneous measurements of cloud properties, humidity, or other variables that characterize the fast feedback processes in the climate system. Similar use can be made of seasonal forecasts, which bring slower feedback processes into play. Systematic biases in seasonal forecasts of climate often reflect problems with the treatment of climate feedback processes in the forecast models.

PRIORITIES IN CLIMATE FEEDBACK RESEARCH

This report reviews the scientific understanding of key feedback processes in the climate system and suggests research activities that will improve our understanding of these processes and our ability to model them effectively in global climate models. In selecting the priority feedbacks, the following criteria were applied:

- the expectation that the feedback process will have a significant effect on the magnitude, timing, or spatial structure of the climate response to human-induced climate forcing during the next century;
- the likely magnitude of the uncertainty of the effect of the feedback process; and
- the probability that a well-focused research effort could over the next several years significantly enhance our understanding of and ability to characterize and perhaps quantify the uncertainties associated with the feedback process.

In addition to these criteria, discussion is limited to feedback processes that are likely to have large-scale effects that would appear in global averages or averages over large areas of at least continental scale. Better knowledge on these large scales should translate into better understanding on smaller scales, but additional uncertainties in local climate arise from local winds, ocean currents, and geography that are not addressed here.

In studying this problem and preparing this report the Panel found that the scientific understanding, observations, and models necessary to understand feedback processes and climate sensitivity overlap significantly with understanding, observing, and modeling climate forcing. Because both factors are changing over time, the transient response of the climate system to gradually increasing forcing must also be considered. Partly for these reasons this report takes a broad view of climate feedback processes and climate sensitivity. It groups feedback processes into three categories: (1) those that primarily affect the magnitude of climate change; (2) those that primarily affect the rate or timing of climate change; and (3) those that primarily affect the spatial patterns of climate change. These categories are also helpful for promoting public understanding of the importance of these processes because they translate into questions like: “How big or important will climate change be?” “How rapidly will climate change?” and “How will climate change in my area?”

The Panel has identified the following key climatic processes or closely related phenomena that it judges to be high-priority research areas, based on the potential contribution to understanding climate evolution over the next 100 years and the potential for rapid scientific progress. The priorities are organized into three categories based on whether their most important effects are on the magnitude, timing, or spatial structure of climate change. More detail supporting these priorities can be found in the body of the report.

1. Feedbacks that primarily affect the magnitude of climate change
    - Cloud, water vapor, and lapse rate feedbacks
    - Ice albedo feedback
    - Biogeochemical feedbacks and the carbon cycle
    - Atmospheric chemical feedbacks
2. Feedbacks that primarily affect the transient response of climate
    - Ocean heat uptake and circulation feedbacks
3. Feedbacks that primarily influence the pattern of climate change
    - Land hydrology and vegetation feedbacks
    - Natural modes of climate system variability

Over the long term all these areas stand to make valuable contributions to understanding climate change. For the near term the two most important areas are (1) cloud, water vapor, and lapse rate feedback and (2) ice-albedo feedbacks, both of which primarily affect the magnitude of climate change.

Feedbacks That Primarily Affect the Magnitude of Climate Change

Feedbacks that primarily affect global climate sensitivity

Cloud, water vapor, and lapse rate feedbacks as a group and ice-albedo feedback are the feedback processes that seem most important in determining the global mean climate sensitivity.

Cloud, Water Vapor, and Lapse Rate Feedbacks

Cloud feedback is one of the key uncertainties in projections of future climates, and is responsible for a large fraction of the model-to-model variation in climate sensitivity. Significant uncertainties remain in water vapor and lapse rate feedback, but these are closely coupled to cloud processes, so we have grouped them together. It is not known whether cloud feedback will increase or decrease global warming, let alone its magnitude.

An accelerated and focused effort to test the simulation of cloud, water vapor, and lapse rate feedbacks in climate models, and their role in climate sensitivity is needed. Such an effort is particularly appropriate now because new climate models that predict cloud properties show a large range of cloud feedback strength, new satellite and surface-based measurements exist to test cloud simulations, and cloud-resolving models have emerged as a tool for understanding the interaction of clouds, water vapor, and lapse rate. Effective synergism among efforts to diagnose observations, to model cloud systems, and to model the global climate is essential. A set of observable metrics should be defined and used to test our understanding of cloud, water vapor, and lapse rate feedbacks. Because of its large contribution to current uncertainty estimates and the potential to make significant progress in the near term, the Panel feels that cloud, water vapor, and lapse rate feedback is the highest priority at this time.

Ice Albedo Feedback

Ice and snow in high latitudes, and in particular sea ice, are important contributors to climate sensitivity through ice albedo feedback, but the magnitude of this feedback remains uncertain. Ice albedo feedback in polar regions is coupled strongly to polar cloud processes and ocean heat transport. Improvements are needed in the parameterization of sea-ice growth, associated heat and freshwater fluxes, surface albedo variations, and polar clouds. Better observations of polar ice distributions and associated atmospheric and oceanic properties is needed. Systematic global observations of sea-ice thickness, polar clouds, and the surface albedo in ice-covered areas are especially important, but a system to make ice thickness measurements is as yet unavailable. Further development and distribution of satellite and in situ datasets describing variations of polar ice and polar clouds should be a priority.

Processes That Feed Back on Climate Forcings

As the climate changes, temperature, precipitation, and circulation changes are likely to change how the climate system deals with the greenhouse gases, aerosols, and surface modifications produced by humans, and this will affect the climate forcing. It is likely that climate change will evoke natural responses in the climate system that will magnify or mute human-produced climate forcing through alterations in greenhouse gases and aerosols.

Biogeochemical Feedbacks and the Carbon Cycle

The global carbon and sulfur cycles contain potentially important feedback processes. There are, however, major gaps in understanding. No definitive explanation has been given for the apparent vast uptake of CO_2 by the terrestrial biosphere, and no confident prediction can be given of future biological uptake or release of CO_2, particularly over the long term. Few observations are available to guide the necessary scaling of vegetation-climate feedbacks from the scale of an individual leaf to a landscape mosaic of vegetation and soils. In the marine realm the strengths of a wide variety of potential feedback mechanisms related to CO_2 uptake and release of dimethylsulfide are yet to be determined.

Research into carbon uptake by the land and ocean as outlined in the U.S. Carbon Cycle Plan (Sarmiento and Wofsy, 1999) and North American Carbon Program (Wofsy and Harriss, 2002) should be undertaken to characterize and reduce the uncertainty associated with carbon uptake feedbacks. The goal is to characterize key atmospheric, biospheric, and oceanic processes that influence the abundance of CO_2, with special attention given to observations that define large-scale, decadal, and longer-term sources and sinks, and to define the influences on these processes of climate, land use, and socioeconomic policies. A high priority is to understand the nature of the Northern Hemisphere carbon sink, so that the evolution of this sink and its relationship to the evolving climate can be better understood. Research outlined in the Surface Ocean Lower Atmosphere Study Science Plan (Liss et al., 2002) will improve understanding of climate-dimethylsulfide feedbacks.

Atmospheric Chemical Feedbacks

Improved understanding of atmospheric chemistry feedbacks is important for producing future climate projections, for understanding the relationship between measured concentrations of greenhouse gases and their emissions, and for formulating control strategies. Both tropospheric and stratospheric chemical processes interact with temperature, humidity, circulation, and air composition changes and may in turn affect Earth's radiative balance. More research on atmospheric chemical feedback processes is required, with the goal of representing these processes more comprehensively in projections of future climate.

The physical and chemical processing of aerosols and trace gases in the atmosphere, the dependence of these processes on climate, and the influence of climate-chemical interactions on the optical properties of aerosols must be elucidated. A more complete understanding of the emissions, atmospheric burden, final sinks, and interactions of carbonaceous and other aerosols with clouds and the hydrologic cycle needs to be developed. Intensive regional measurement campaigns (ground-based, airborne, satellite) should be conducted that are designed from the start with guidance from global aerosols models so that the improved knowledge of the processes can be directly applied in the predictive models that are used to assess future climate change scenarios.

The key processes that control the abundance of tropospheric ozone and its interactions with climate change also need to be better understood, including but not limited to stratospheric influx; natural and anthropogenic emissions of precursor species such as NO_x, CO, and volatile organic carbon; the net export of ozone produced in biomass burning and urban plumes; the loss of ozone at the surface, and the dependence of all these processes on climate change. The chemical feedbacks that can lead to changes in the atmospheric lifetime of CH_4 also need to be identified and quantified.

Feedbacks That Primarily Affect the Transient Response of Climate

Ocean Heat Uptake and Circulation Feedbacks

Many climate models predict that the rate of warming over the next 30 years will be much larger than the rate of warming observed over the past century. The rate of warming is important for its effect on human affairs and natural ecology, but it is also very important in continuing efforts to understand the relative roles of feedbacks, forcings, and heat storage in setting the observed warming rate. These efforts are important both for detection and attribution of climate change and for improving projections of future climate. The transient response to changed climate forcing involves important feedback processes, because the evolving climate may alter the rate of heat uptake by the ocean through increased thermal stratification of the ocean, or through the effect of changes in surface precipitation and evaporation on ocean salinity and density.

To better represent the exchange of heat and carbon dioxide at the air-sea interface, physical representations of upper ocean processes need to be improved in climate models based on experimental studies of the vertical structure of temperature, absorption of solar radiation, and salinity representative of different ocean environments, including high northern and southern latitudes. Improved definition of the time-dependent temperature and salinity distribution in the global ocean is essential, including the air-sea fluxes of heat and freshwater. This will require full implementation of a system with the capabilities of the current and planned ocean-observing satellites, the Argo global array of profiling floats, the in situ tropical ocean observation networks, and a strategy for monitoring key regions of the ocean where deep-water formation occurs, such as the Labrador, Greenland-Iceland-Norwegian, Weddell, and Ross Seas.

Feedbacks That Primarily Influence the Pattern of Climate Change

Although the change in global mean climate is important and in some ways easier to project, regional changes are of great practical significance and may provide important clues to understanding the climate system.

Land Hydrology and Vegetation Feedbacks

Feedback processes over land are critically important to understanding the climate response over land and its effect on humans. Global climate change may initiate local changes in hydrology and surface albedo that feed back to produce larger or smaller local changes in temperature, precipitation, evaporation, soil moisture, and vegetation. The responses of the hydrologic and energy cycles over land play a critical role in determining the impacts of climate change on water resources, carbon stocks, and agriculture, yet these responses vary widely among different climate models. Basic processes such as the response of the land-atmosphere system to diurnal variations of insolation are poorly simulated in current climate models. The melting of snow and ice and associated hydrologic and radiative consequences also tend to be poorly simulated. Dynamic vegetation modeling is also in its very early stages.

An integrated analysis is required of the diurnal and annual cycles of the energy, water, and carbon budgets at the land-surface and through the atmospheric boundary layer for different ecosystems and climatic regimes, including managed ecosystems like irrigated cropland. This analysis—aimed at improving theoretical understanding and model parameterizations—needs to fully integrate land and atmosphere processes and use carefully designed observational metrics to test modeled processes. These models must account for time-varying land surface properties. Sustained multiyear observations of terrestrial ecosystems, their functioning, and their role in the climate system that will contribute to the development and improvement of process-oriented vegetation models for use with climate models should be encouraged.

Natural Modes of Climate System Variability

Radiatively induced greenhouse warming is not the only effect of greenhouse gas buildup. There is a growing body of evidence that suggests that human activities may also be capable of changing the time-averaged states of the natural modes of variability of the climate system, most notably, the El Niño-Southern Oscillation (ENSO) and the high-latitude northern and southern hemisphere annular modes. An understanding of these modes and how they react to anthropogenic forcing is essential for detection and attribution of global climate change and for interpreting the role of feedbacks. In addition, the natural variability of these modes on a year-to-year time scale provides a testbed for model parameterizations of feedbacks.

A tightly integrated effort is needed to close the major gaps in the understanding and modeling of the relationships between natural modes of climate variability and climate change. This effort should integrate data acquisition, analysis, and modeling and should include interactive interfaces among national and international programs that are pursuing seasonal forecasting, climate change feedbacks research, climate change simulation, and climate change detection and attribution (NRC, 2001d).

Chapter 1 provides introductory materials as context for understanding the need for a national research strategy in climate feedbacks research. Chapters 2 through 8 provide expanded discussions of the key climate feedback processes that the Panel believes are most in need of study. Chapter 9 summarizes the main recommendations from the chapters.

Each chapter is structured somewhat differently, in part because the research needs are different in each area. However, each discussion is intended to leave the reader with a sense of the key processes that are important role in determining the climatic response to a greenhouse gas forcing. Each discussion outlines some of the most important first steps that should be taken to better characterize and hopefully reduce the uncertainty associated with the various feedbacks. These steps include, in general terms, the types of observations and metrics that can be used to improve both understanding and model representations, as well as to test simulations.

1

INTRODUCTION

The consensus view of scientists is that human activities are changing Earth's climate and that this could have very important consequences for human life and natural ecosystems (IPCC, 2001b; NRC, 2002). Projections[1] of how climate might change as a result of human activities remain uncertain, however. The International Panel on Climate Change (IPPC) Third Assessment Report (TAR) projects that annually and globally averaged surface temperature will increase by 1.4˚C to 5.8˚C during the interval between 1990 and 2100 (Cubasch et al., 2001). The large range of possible warming results in approximately equal measure from two sources.

First, the rate at which humans will release greenhouse gases and make other changes in the natural environment of Earth in the future is difficult to predict. The future rates of human modification of the environment depend on social, economic, and political processes as well as technological innovation and diffusion, and are unknown. Policy makers may make different choices if scientists provide credible information about the magnitude and structure of the climate response to greenhouse gas releases.

The second source of uncertainty is how the climate system of Earth will respond to human forcing. Interactions among physical, chemical, and biological processes that determine the response of the climate system to human activities are not fully understood. If the carbon dioxide concentration in the atmosphere were doubled and the climate were allowed sufficient time to come into a new equilibrium, the projected uncertainty in the warming of the global mean surface temperature would still be large

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[1] In this document we have generally tried to follow the IPCC practice of using the word "projection" when referring to estimates of future climates that are hypothetical in the sense that they depend on an assumption of a particular scenario for emissions (and hence radiative forcing). We use the word "prediction" when the answer is not contingent on a climate-forcing scenario or the climate-forcing scenario is considered fixed, such as in the problem of calculating the equilibrium response to doubled CO_2.

(1.5°C to 4.5°C according to the Intergovernmental Panel on Climate Change) (IPCC, 2001a). Our inability to reliably determine the influence of various feedback processes is one of the most important reasons why projections of possible future climate change show such wide variations. Scientific research can provide knowledge that will help refine and focus these projections so that they become more accurate over time.

Climate scientists often separate influences on climate change into forcings and feedbacks. Climate forcings are changes that initiate outside of the naturally evolving climate system, and can be either natural or human-caused (See Table 1.1). Processes in the climate system that can either amplify or damp the system's response to changed forcings are known as feedbacks. Feedbacks are interactions in the climate system between the variables defining the state of the atmosphere, ocean, and land surface.

The range of possible outcomes in climate change projections that results from the internal dynamics of the climate system is the result of feedback processes and our inability to capture these adequately in models. A feedback process is a process whereby a change in one variable, such as carbon dioxide concentration, causes a change in temperature, which causes a change in a third variable, such as water vapor, which in turn causes a further change in temperature. Climate models suggest that the temperature change enhancement associated with feedback processes is greater than the temperature change resulting from the direct effect of the carbon dioxide doubling without feedbacks (IPCC, 2001a). Stott and Kettleborough (2002) find that the magnitude of global warming over the next 40 years is insensitive to the rate of greenhouse gas releases; in their study the range of possible warmings is determined by the range of estimates of the strength of climate feedbacks and not by the range of estimates of climate forcing. Therefore, study of climate feedbacks and climate sensitivity is very important for projecting climate changes over the next 40 years.

Even in a simple linear analysis the temperature response is not linear in the strengths of the feedbacks, because all the other feedback processes modify the temperature change associated with one feedback process (Hansen et al., 1984). In a system with a strong positive feedback, such as water vapor feedback in the climate system, the strong positive feedback process amplifies the changes associated with weaker feedback processes (See Box 1.1).

The integrated effect of climate feedback processes on climate sensitivity can be estimated by using the observed record of global mean temperature over the past 120 years (IPCC, 2001a). This method requires estimates of the climate forcing, climate sensitivity, and the uptake of heat

TABLE 1.1 Climate Forcing Variables Compared to Climate State Variables[a]

Climate Forcing Variables	Climate System State Variables
Solar irradiance	Temperature of air, land, and water
Volcanic eruptions	Precipitation and snow cover
Greenhouse gas production by humans	Humidity, clouds, and winds
Aerosol production by humans	Ocean currents, salinity, and ice cover
Reactive gas production by humans	Soil moisture and vegetation properties
Land surface modification by humans	Aerosol distribution
	Atmospheric trace gas concentration

[a]The variables in the left column are natural and human-caused climate forcings that are defined to be outside the climate system for the purposes of this report. The processes that couple the climate system variables in the right column can result in climate feedback that will determine the response of climate to forcing.

by the climate system, and each of these factors is uncertain. Consequently, the range of probable future climates is only loosely constrained by models fitted to the instrumental record of global mean temperature. Andronova and Schlesinger (2001) used a Monte Carlo simulation with a simple climate system model to estimate a probability distribution function for climate sensitivity. Climate sensitivity is here defined to be the equilibrium response of global mean surface temperature to doubling carbon dioxide. They concluded that there is a 54 percent likelihood that the actual climate sensitivity lies outside the range of 1.5-4.5°C and that the 90 percent confidence interval for climate sensitivity is 1.0-9.3°C. Knutti et al. (2002) found a 40 percent probability that the warming will exceed the IPCC estimates, but only a 5 percent probability that the warming will be less than the IPCC lower limit. Forest et al. (2002) found similarly that the 5 percent and 95 percent confidence limits on the climate sensitivity are 1.4°K to 7.7°K, compared to the 1.5-4.5°K range stated by IPCC. Use of the instrumental record of global mean temperature cannot constrain climate sensitivity to a narrow range because the climate-forcing magnitude, amount of heat storage, and even the temperature record itself are not known with sufficient precision.

An enhanced effort to understand and model the most important climate feedback processes is needed to improve our fundamental knowledge and will lead to better characterizations of the climate system, potentially reducing the wide ranges now seen in climate change projections. Improved understanding, combined with more rigorous comparison of observed and modeled feedback processes, should lead to more confidence in climate model projections. This approach should be pursued in parallel with the system level approach based on the global mean temperature record. Thus a key finding of this report is that an enhanced research effort is needed to better observe, understand, and model key climate feedback processes.

Research on climate feedback processes should be designed to

- integrate observational and modeling efforts toward understanding and modeling of climate feedback processes;
- integrate the subdisciplines of climate science for a comprehensive study of the key climate feedback processes; and
- integrate different time scales of weather and climate variability into studies of climate feedback processes.

Although observations are used to test the climatological statistics derived from climate simulations, more attention needs to be given to using data to test the simulation of feedback processes in these models and their role in determining climate sensitivity. To do this will require greater synergy between the efforts of observational scientists and modelers. In addition, because climate change feedbacks often incorporate processes from different disciplines, such as sea-ice processes and ocean circulation, or land surface processes and cloud processes, climate feedbacks research will also require greater synergy between traditional subdisciplines in climate science.

Many climate feedback processes operate on time scales short enough to be tested effectively by comparing numerical weather forecasts with instantaneous data. For example, the ability of models to simulate the occurrence of frontal clouds in middle latitudes can be better understood by comparing instantaneous fields observed from satellites with instantaneous fields simulated in weather prediction models. Similar use can be made of seasonal forecasts, which bring slower feedback processes into play. Systematic biases in seasonal forecasts of climate often reflect problems with the treatment of climate feedback processes in the forecast models. For example, Li and Philander (1996) found that the improved simulation of marine boundary layer clouds was important in simulating the annual cycle in the tropical Pacific and its relation to the El Niño phenomenon. The interannual variations associated with ENSO events can also be used to better understand climate and carbon cycle coupling in the ocean and on land, since the growth rate of carbon dioxide in the atmosphere is highly correlated with interannual variations in tropical Pacific sea surface temperature (e.g., Jones et al., 2001).

BOX 1.1
Classical Treatment of Climate Sensitivity and Feedback Processes

One can write a simple linear expression that relates the change in equilibrium temperature ΔT_{eq} to the magnitude of the applied forcing, ΔQ Wm^{-2}.

$$\Delta T_{eq} = \lambda \, \Delta Q \tag{1}$$

The climate sensitivity parameter λ measures the ratio of the temperature change to the applied climate forcing. Feedback processes alter the relationship between the magnitude of forcing and the magnitude of the climate response.

The most fundamental feedback in the climate system is the temperature dependence of radiative emission. As objects get warmer they emit more radiant energy, as expressed by the Stefan-Boltzmann law of blackbody emission, *Irradiance* = σT^4. If a linear model is assumed, and only the temperature dependence of blackbody emission is considered, then the sensitivity parameter is $\lambda_o = (4\sigma T_e^3)^{-1}$. Assuming an emissivity of one and an emission temperature of 255K, this gives a basic sensitivity parameter of $\lambda_o = 0.26K\,(Wm^{-2})^{-1}$. From (1) then we could write

$$\Delta T_o = \lambda_o \, \Delta Q \tag{2}$$

If a forcing of 4 Wm^{-2} is applied to this system, then the expected equilibrium surface temperature change is about 1°K.

The gain factor, *g*, is the fraction of the equilibrium climate change associated with feedback processes in addition to basic blackbody feedback.

$$g = \frac{\Delta T_{eq} - \Delta T_o}{\Delta T_{eq}} = \frac{\Delta T_{feedbacks}}{\Delta T_{eq}} \tag{3}$$

It can be shown that

$$\Delta T_{eq} = \frac{\Delta T_o}{1 - \sum_i g_i}, \tag{4}$$

where a number of different feedback processes with feedback factors, g_i, are assumed to be linearly additive. If the gain is zero, the response is just ΔT_o, and as the gain approaches one the response becomes very large.

If the feedbacks are considered to act independently, then the gain factors for individual feedback processes are additive and their importance can be measured by their relative contributions to the total gain.

$$g = g_{water\ vapor} + g_{cloud} + g_{surface\ ice} + g_{lapse\ rate} + g_{other} \tag{5}$$

The gain factor for water vapor feedback is about 0.5, which according to (4), will double the temperature response to climate forcing, changing the equilibrium response to doubled carbon dioxide from 1˚C to 2˚C. If an additional feedback only half as strong as water vapor feedback is added to the system, with a gain factor of ±0.25, then the temperature response will be 4.0˚C if the weaker feedback is positive, and 1.3˚C if the weaker feedback is negative. Thus, once a strong positive feedback is present in the system, the effects of the other feedback processes are amplified.

These equations assume small perturbations of the equilibrium climate and (5) assumes that the feedback processes are independent and additive. Climate feedback processes do interact with each other in important ways. Moreover, the climate will not be in equilibrium for the next several centuries, but rather will be responding in a transient way to changing conditions. For these reasons the formalism of linear feedback analysis described here can be used only as a rough guide to the relative importance of feedback processes.

2

CLOUD, WATER VAPOR, AND LAPSE RATE FEEDBACKS

SUMMARY

Cloud feedback and its association with water vapor feedback and lapse rate feedback appear to be the largest contributors to uncertainty in climate sensitivity and is therefore one of the key uncertainties in projections of future climates. Improvements are particularly needed in the treatment of marine boundary layer clouds and tropical convective clouds. Progress on better understanding cloud feedback seems possible now because: (1) current climate models have predictive cloud schemes that produce important effects on climate sensitivity; (2) new data are becoming available that can be used to test these new climate models; and (3) cloud-resolving models have emerged as a new tool for understanding and testing cloud feedback processes in climate models.

An accelerated, focused effort to test the simulation of cloud, water vapor, and lapse rate feedbacks in climate models, and their role in climate sensitivity should be initiated. Existing and planned observations should be used in this new emphasis to test the simulation of clouds, water vapor, and lapse rate in climate models and the response of these variables to known forcings. Effective collaboration among efforts to diagnose observations, to model cloud systems, and to model the global climate is essential. A set of observable metrics should be used to evaluate the success of these activities.

WATER VAPOR

Water vapor feedback is the most important positive feedback in climate models. It is important in itself, and also because it amplifies the effect of every other feedback and uncertainty in the climate system. Most modeling and observational studies suggest that the water vapor feedback in current climate models has the correct sign and magnitude (Held and Soden, 2000). The magnitude of water vapor feedback is so large, however, that modest uncertainty in water vapor feedback can still have a significant effect on the magnitude of climate change.

It is known from basic physical principles that the vapor pressure in equilibrium with a water surface increases exponentially with temperature at a rate such that a 1 percent change in absolute temperature, a change of about 3°C, is associated with an approximately 20 percent increase in saturation vapor pressure. Because water vapor is the most important greenhouse gas in Earth's atmosphere, the dependence of vapor pressure on temperature forms the basis of one of the strongest positive feedbacks in the climate system. If the relative humidity distribution remains approximately constant as temperature and specific humidity increase, then water vapor greenhouse feedback nearly doubles the sensitivity of climate above what it would be in the absence of water vapor feedback.

On the largest spatial scales, existing data and current climate models are basically consistent with the assumption that on interannual time scales, relative humidity is more or less constant (Soden et al., 2002; Wentz and Schabel, 2000). However, local diurnal and seasonal relative humidity variations are significant, and analysis of climate model simulations of these features is needed. Furthermore, the relationship between temperature and humidity on interannual and longer time scales shows substantial vertical and regional structure, which models are only partly successful in simulating (Bates and Jackson, 1997; Bauer et al., 2002; Ross et al., 2002).

As shown by modeling and observational studies (Del Genio et al., 1991; Harries, 1997; Held and Soden, 2000; Shine and Sinha, 1991; Soden et al., 2002), water vapor variations in the tropical upper troposphere seem to have the strongest effect on outgoing long-wave radiation. However, the relative importance of water vapor in different regions of the atmosphere is sensitive to the assumptions made about clouds and about the variations (or lack thereof) of relative humidity with temperature. In fact, according to Harries (1997), "[U]ncertainties of only a few percent in knowledge of the humidity distribution in the atmosphere could produce changes to the outgoing spectrum of similar magnitude to that caused by doubling carbon dioxide in the atmosphere," underscoring the importance of reliable upper tropospheric water vapor observations.

Uncertainty about water vapor feedback rests primarily on the question of whether the relative humidity distribution might change in an altered climate state. Several hypotheses have been put forward describing mechanisms that could alter the relative humidity distribution in a warmed world. The mechanisms that seem most likely to be meaningful are those that may govern the relationship between the area of moist and dry regions in the upper troposphere of the tropics (Lindzen et al., 2001; Pierrehumbert, 1995). In the tropics the greenhouse effect is strong, and large contrasts in upper tropospheric relative humidity are sustained between regions of large-scale ascent and descent. So far, no mechanism has been demonstrated to operate that would provide a significantly more reliable projection than an assumption of constant relative humidity distribution. Nonetheless, the factors that influence water vapor distribution need further study.

One useful metric for evaluating the question of whether relative humidity will change was put forward by Inamdar and Ramanathan (1998). Using Earth Radiation Budget Experiment (ERBE) data they examined the relationship between outgoing long-wave radiation at the top of the clear atmosphere and surface temperature. They found the slope of the regression line between these two variables to be consistent with an assumption of fixed relative humidity (vs. absolute humidity). Using this approach it is possible to compute a gain factor of the clear-sky water vapor feedback. Gain factors determined using this and other observational approaches should be compared with the factors similarly derived from models. This approach is discussed here for to illustrate only one of the many approaches that can be used to assess the ability of models to faithfully represent water vapor feedbacks.

Understanding of the water vapor distribution is being hindered by a lack of accurate measurements of water vapor concentration with sufficient spatial and temporal resolution and global coverage (Kley et al., 2000). Accurate measurements of the water vapor distribution can be used to test understanding of the mechanisms that determine its distribution, and also test to see if the increase of water vapor with time is consistent with models of climate change. *An integrated water vapor observing system should be developed, which has sufficient accuracy to measure decadal trends in the water vapor distribution and sufficient spatial resolution to test mechanisms by which that distribution is maintained.* It should include a network of in situ sounding systems capable of measuring water vapor throughout the troposphere and lower stratosphere, complemented by ground-based remote sensors (such as have already been deployed at Atmospheric Radiation Measurement Project Cloud and Radiation Testbed (ARM CART) sites). These observations would allow quantification of temporal and vertical water vapor variations and would allow calibration and validation of satellite observations, which would extend the global coverage of the observing system.

The global radiosonde network cannot be relied upon for precise water vapor observations, unless substantial improvements are made to ensure higher quality observations in the upper troposphere and in other cold (and dry) regions, and to ensure the long-term continuity of the observations. Expansion of the program for special water vapor soundings of the troposphere and stratosphere (e.g., Oltmans and Hofmann, 1995) to more sites (currently only Boulder is routinely observed) would be very beneficial. These should include both oceanic and continental regions, at a variety of latitudes. Efforts to consolidate and quality-control water vapor observations from different sources (e.g., the NASA Water Vapor Project [NVaP], Randel et al., 1996) should also be encouraged, so that water vapor variability can be examined in conjunction with variations in other atmospheric variables, particularly temperature and radiation. The water vapor observing system should be closely linked to a global cloud, aerosol, and precipitation observing system. Many of the issues mentioned above are discussed in greater detail in a report by the National Research Council (NRC) on the Global Energy and Water Cycle Experiment (GEWEX) Global Water Vapor Project (NRC, 1999c).

LAPSE RATE FEEDBACK

The strength of Earth's greenhouse effect depends on the fact that the temperature decreases with height in the troposphere, so that emission from water vapor and clouds in the colder upper troposphere is less than that from the surface. A stronger lapse rate (the rate of decrease of temperature with altitude) gives rise to a stronger greenhouse effect and a warmer surface, all else being equal. If the lapse rate changes systematically with the surface temperature, then a potentially strong lapse rate feedback may exist.

Radiative processes, large-scale dynamical processes, and convection determine the lapse rate. Radiative processes generally cool the atmosphere and heat the surface, and convection and large-scale motions in the atmosphere generally move heat upward. In the tropics the lapse rate generally follows the moist adiabatic lapse rate, the rate at which saturated air parcels cool with altitude as they are raised adiabatically. The moist adiabatic lapse rate decreases with increasing surface temperature, so by itself lapse rate feedback is expected to be negative in the tropics (Hansen et al., 1984; Wetherald and Manabe, 1986).

If the assumption of fixed relative humidity is a good approximation, then the water vapor feedback is partially cancelled by the lapse rate feedback (Cess, 1975). If the lapse rate is reduced, then the air at altitude is warmer. The warmer air contains more water vapor. The decreased greenhouse effect caused by a weaker lapse rate is offset by the increased greenhouse effect from larger amounts of water vapor at higher altitudes.

Patterns of vertical temperature structure change are one of the few parameters widely used to detect and attribute climate change to particular forcings, or to natural variability (e.g., Tett et al., 2002). (Surface temperature changes are the other main detection parameter.) If climate models correctly simulate climate feedback mechanisms, they should correctly reproduce the change in vertical temperature structure associated with different climate forcings. Thus, changes in lapse rate are indicators both of the strength of lapse rate feedback and of the response to climate forcings.

Climate models generally reproduce the observed lapse rate in the tropics and elsewhere through the incorporation of large-scale dynamics and parameterized convection and radiation. Some observations suggest relationships between surface temperature trends and temperature trends in the free troposphere that seem inconsistent with the behavior of current climate models (NRC, 2000a; Santer et al., 2000). It is still unclear whether these apparent inconsistencies are the result of a measurement problem or a failure of our understanding of the climate system.

Unfortunately, current upper-air temperature observations are not well suited to determining lapse rate changes. The vertical resolution of satellite observations is too coarse for accurate lapse rate computations, although newer instruments (e.g., the Advanced Microwave Sounding Unit) provide better vertical resolution than older ones (e.g., the Microwave Sounding Unit). Both satellite and radiosonde observations are hampered by time-varying biases, which are very difficult to remove (NRC, 2000a). Lapse rate trends are particularly sensitive to attempts to remove these biases (Lanzante et al., in press). Similarly, trends in measures of atmospheric instability and convection that are related to lapse rate (e.g., Convective Available Potential Energy and Convective Inhibition) are affected by radiosonde data inhomogeneities (Gettelman et al., in press). *Thus, to improve our ability to diagnose lapse rate feedback and to detect changes in the vertical temperature structure of the atmosphere, improved long-term upper-air temperature soundings are required.* The observations must be of sufficient precision to measure decadal trends in temperature (and water vapor) distributions and sufficient spatial resolution to test mechanisms by which those distributions are maintained. More information concerning upper-air temperature monitoring requirements can be found in NRC (2000c).

Using the improved observations that are recommended here, correlation statistics of temperature, water vapor, and clouds on various time and space scales should be employed to rigorously diagnose the ability of models to simulate the feedbacks that underpin interannual variability of the lapse rate and water vapor distributions. Extending the work of, for example, Ross et al. (2002), Sun and Held (1996), and Sun and Oort (1995), these analyses should be focused not only on improving understanding of the feedback processes and their representation in models but also on deriving new, parsimonious model representations of these processes. Several existing national and international programs (e.g., ARM and GEWEX) could be very helpful in facilitating this work.

CLOUD FEEDBACKS

Because clouds are generally colder than the surface they overlie and because they absorb and emit terrestrial radiation, the presence of clouds generally reduces the energy emitted to space from Earth relative to the emission from Earth when clouds are absent. For terrestrial radiation, clouds thus act very much like greenhouse gases and warm the surface of Earth. Clouds also reflect solar radiation very effectively, which reduces the amount of solar energy reaching the surface of Earth. This tends to cool the surface. Different cloud types have different effects on the energy balance of Earth (Hartmann et al., 1992). If the structure or area coverage of clouds change with the climate, they have the potential to provide a very large feedback and either greatly increase or decrease the response of the climate to human-caused forcing. At this time both the magnitude and sign of cloud feedback effects on the global mean response to human forcing are uncertain.

It has been well documented that climate models are sensitive to the representation of clouds and their radiative properties (e.g., Cess et al., 1990; Paltridge, 1980; Schneider, 1972; Senior and Mitchell, 1993; Stocker et al., 2001; Webster and Stephens, 1984). A relatively modest change in cloud properties can have a significant effect on Earth’s energy balance. In addition to their influence on the radiative processes that define the energy balance of the planet, clouds processes are integral to the cycling of water between the surface and the atmosphere.

A striking example of the contribution of cloud feedbacks to uncertainty in climate sensitivity is exhibited by comparison of the current climate models at the Geophysical Fluid Dynamics Laboratory (GFDL) and the National Center for Atmospheric Research (NCAR). The GFDL model has a rather high sensitivity (near 4˚C for doubled CO_2) while the NCAR model has a rather low sensitivity (near 2˚C). The primary reason for this difference is in the response of low marine boundary layer clouds in the two models. As the climate warms, marine boundary layer clouds decrease in the GFDL model and increase in the NCAR model. Comparison of these two models with observations, theory, and cloud-resolving model computations should lead to much greater understanding of the response of marine boundary layer clouds to changing climate, and a consequent reduction in uncertainty of climate sensitivity.

Another key uncertainty in cloud-climate interactions is the response of anvil clouds to surface temperature. It is unknown whether anvil clouds expand or contract when surface temperature warms. A combination of detailed observational studies and cloud-resolving modeling studies can shed light on this issue. Some models incorporate a cloud optical thickness feedback that assumes cloud water content will increase with temperature following the saturation vapor pressure, but satellite and in situ data do not show an obvious signal of this nature, and low clouds show an apparent signature in the opposite sense (Tselioudis et al., 1992).

Clouds couple many feedback processes in the climate system. Some of the interactions of clouds with other feedback processes are illustrated below.

Clouds and Water Vapor Feedback

The formation and evaporation of clouds are intimately tied to the amount of water vapor in the atmosphere. The amount of water vapor and its vertical distribution are also influenced by the amount and distribution of clouds. For example, a number of studies have shown very clearly how the water vapor in the middle to upper troposphere is sensitive to the presence of ice crystals, the nature of the microphysical properties of these ice crystals, and the way these crystals fall in the atmosphere. (e.g. Donner et al., 1997; Stephens et al., 1998). Vertical transport of water in both vapor and ice form by convection in the tropics is an important source for upper tropospheric water vapor (Pierrehumbert and Roca, 1998; Salathé and Hartmann, 1997; Udelhofen and Hartmann, 1995). The broad role of water vapor feedback in climate change and the specific importance of upper tropospheric water vapor cannot be divorced from the associated role of clouds and cloud feedbacks.

Clouds, Lapse Rate, and Precipitation

The vertical distribution of clouds is an important factor in determining radiative heating. In turn, radiative heating is closely coupled to the temperature profile, convective heating, and precipitation. A number of modeling studies have illustrated how the radiative effect of cloudiness, the vertical profile of temperature, convection, and precipitation are tightly coupled (e.g. Fowler and Randall, 1996; Liang and Wang, 1997; Ma et al., 1994; and Slingo and Slingo, 1988).

Clouds and Sea-Ice Albedo

Ice albedo feedbacks that may occur in polar regions are tightly coupled to the surface energy balance and to clouds. Clouds can change the heat balance of the surface and influence surface ice formation and melting, and overlying clouds can mask the effect of surface ice on the albedo of Earth. A complex coupling thus exists between cloud feedbacks and ice-albedo feedback processes (see Chapter 4).

Clouds and Soil Moisture

The feedbacks involving soil moisture and evaporation are intimately tied to the hydrological cycle over land (see Chapter 6). Clouds are central to soil moisture feedbacks both through their profound influence on the surface energy balance and through their association with precipitation. The relationships among soil moisture, boundary layer humidity, and cloudiness serves as a possible mechanism for a strong, coupled feedback between clouds and the underlying land surface.

Clouds, Chemistry, and the Marine Biosphere

The effect of changing concentrations of cloud and ice condensation nuclei (CCN and IN, respectively) on clouds and precipitation has received much attention recently (e.g., Durkee et al., 2000). The association between aerosol forcing, cloud nuclei, and cloud processes provides a path that links clouds to oceanic emissions of dimethyl sulphide (DMS) and to gas phase chemistry (e.g., Charlson et al., 1987; Coakley et al., 1987). The consequences of these links are twofold. In the case of DMS emissions they provide additional feedback mechanisms if the production of nuclei depends on temperature or solar radiation reaching the surface. In the case of increasing aerosols the relation between aerosols and condensation nuclei connects cloud processes to the broader problem of estimating climate forcing through the so-called indirect aerosol forcing.

Cloud Radiation Processes

Clouds affect both the radiation balance at the top of the atmosphere and the distribution of radiative heating between the atmosphere and surface.

The Effects of Clouds on the Top-of-the-Atmosphere Energy Budget

The radiation budget of Earth is the difference between solar radiation absorbed by the planet and terrestrial infrared (IR) radiation emitted to space. Clouds affect this budget by reflecting sunlight back to space (the albedo effect of clouds), thereby decreasing the solar radiation absorbed by the planet, and by absorbing thermal radiation emitted by the surface and lower atmosphere (the greenhouse effect of clouds), thereby reducing the radiation emitted to space. The balance between these negative and positive effects on the radiation balance depends on the type and location of the cloud in question (Hartmann et al., 1992). The albedo effect of low clouds over ocean, for example, tend to dominate over their greenhouse effect and produce a negative impact on Earth's energy balance, whereas the reverse is generally true for high, thin cirrus. Satellite experiments like ERBE and Clouds and the Earth's Radiant Energy System (CERES) provide a quantitative measure of the instantaneous effects of clouds on the top-of-the-atmosphere (TOA) radiation balance and confirm our understanding of the effect of different cloud types on this budget. Although data collected from these satellite experiments provide an important source of information for testing models, they do not sufficiently constrain critical assumptions about the treatment of cloud processes in climate models.

Measurements of radiative properties and inferred column-integrated cloud optical properties as have been made over the past 20 years are insufficient to advance understanding and modeling of cloud feedbacks. What is needed are measurements of those key variables prognosed from models that describe the underlying cloud physical processes. These variables include the mass of liquid water and ice in clouds and precipitation and how these water masses mutate, passing from the cloud to the precipitation state. New global observations that will be relevant to understanding cloud feedbacks and validating global climate models are becoming available from new satellite measurements obtained from NASA's Earth Observing System. New global data on cloud properties, water vapor, and aerosols instruments is expected from instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multiangle Imaging SpectroRadiometer (MISR), and the Advanced Infrared Sounder (AIRS) (Aumann et al., 2003; Diner et al., 2002; King et al., 2003) (See also the subsequent, broader description of the global-scale observations that are required.)

The Effects of Clouds on the Partitioning of the Radiation in the Atmosphere and at the Surface

The reflection of solar radiation by clouds causes a strong reduction in the energy balance of the surface because most of the solar radiation that is not reflected is absorbed at the surface. At high latitudes where insolation is weak and the atmosphere is relatively dry, the addition of clouds can heat the surface through increased downward IR emission by the atmosphere. Whether cloud layers heat or cool the atmosphere relative to clear skies, and the amount of this heating or cooling that takes place is largely determined by the vertical location and distribution of the clouds. High clouds tend to warm the atmosphere relative to surrounding clear skies, whereas low clouds tend to enhance the cooling of the atmosphere. While the total incoming and outgoing radiation at the TOA can be measured, the amount of radiative heating that occurs within the atmosphere versus how much heating occurs at the surface cannot be directly measured. Thus, model parameterizations of the internal heating of the climate system cannot be tightly constrained by observations. This shortcoming is a significant source of uncertainty in understanding cloud feedbacks.

Clouds and the Large-Scale Circulation: The Cloud Parameterization Problem

Developing and testing understanding of cloud fields and their interactions with the larger-scale environment has proven to be difficult. Many of the processes that control cloud feedbacks occur on scales smaller than those resolved by large-scale models in use today. These processes are thus parameterized, meaning that they are expressed in terms of large-scale quantities that are resolved by models. The influence of these large-scale properties on smaller-scale parameterized processes, and the subsequent feedback of the latter to the large scale, is referred to as the cloud parameterization problem. Three types of processes are critical: (1) cloud physical processes, including processes that govern the life-cycle of cloud-scale phenomena, (2) cloud radiative process, and (3) large-scale cloud thermodynamical processes that determine the heating in the climate systems and the associated atmospheric circulation.

Quantifying Processes That Govern Life Cycles of Large-Scale Cloud Systems

Although the cloud processes that influence the radiation budget in principle are numerous and occur over a vast range of scales, the dominant scale of variability of cloudiness is the synoptic scale (e.g., Rossow and Cairns, 1995). Therefore, key first steps in understanding cloud feedbacks in the global climate system require understanding processes that organize clouds on this same large scale. These processes involve connections between the general circulation of the atmosphere and the weather systems that are a manifestation of this circulation, the formation and evolution of the large cloud systems associated with these weather systems, and the latent heating and radiative heating distributions organized on this larger scale. Because the processes that govern cloud evolution are modulated by the weather systems in which they are embedded, a fruitful strategy should embrace the study of weather. Numerical weather prediction models, related data assimilation activities, and synoptic data on weather and clouds should be used to understand and model cloud and precipitation evolution over a range of time scales from hours to weeks.

Day-to-day weather variations are carefully observed, assimilated into models, and used to make predictions. Because day-to-day weather variations include variations in cloud amount and type, these variations should be used to test the ability of climate models to predict cloud variations on these time scales (e.g., the testing of cloud simulations at the ECMWF [Hogan et al., 2001; Klein and Jacob, 1999]). This strategy has several advantages.

- Cloud feedbacks are currently diagnosed primarily by using coarse resolution climate models and even simpler one-dimensional equilibrium models. The use of Numerical Weather Prediction (NWP) models and forecast validation will allow day-to-day weather variations and their association with cloud variations to be used to validate models.

- Connecting feedback diagnostic studies to NWP and data assimilation efforts introduces a certain rigor to the exercise of model-data comparison by tying the analysis methods more tightly to the observations and allowing many more realizations.
- NWP and the data assimilation process offers a consistent way of obtaining integrated datasets necessary for understanding processes deemed important to cloud feedback.

Quantifying the Relationship Between Cloudiness and Radiative and Latent Heating

A strategy for understanding the relationship between clouds and precipitation in more quantitative detail requires a change in current research practices. Research activities and observational practices for clouds and precipitation are typically designed in isolation from each other. The parameterization of the radiative effect of clouds is often treated separately from the parameterization of precipitation. Advances will occur with the adoption of a more integrated approach toward developing global cloud and precipitation observing and projection systems.

Global precipitation, water vapor, and cloud-observing systems must be designed in concert with one another so that the interconnectivity of these processes can be better observed and understood. Similarly, parameterization and projection systems must address these variables as part of an interconnected system.

WHY HAS PROGRESS ON CLOUD, WATER VAPOR, AND LAPSE RATE FEEDBACKS BEEN SO ELUSIVE?

The 1979 NRC report on carbon dioxide and climate contains the following statement in reference to cloud effects on climate change:

> Trustworthy answers can be obtained only through comprehensive numerical modeling of the general circulations of the atmosphere and oceans together with validation by comparison of the observed with the model-produced cloud types and amounts.

This strategy remains valid today, but it has not yet been executed. Three obstacles have heretofore limited the advancement of understanding of cloud, water vapor and lapse rate feedbacks: inadequate data, incomplete theories, and untested projections.

Inadequate Data for Developing and Testing Hypotheses

Measurements of Earth's energy budget with sufficient accuracy for climate studies began about 1985 with the Earth Radiation Budget Experiment. Measurements of water vapor and upper tropospheric temperature need to be improved in both accuracy and sampling. At the present time cloud data come from two sources: surface visual observations (Hahn and Warren, 1999) and meteorological imaging instruments on operational satellites (Rossow and Schiffer, 1999). The International Satellite Cloud Climatology Project (ISCCP) data provide estimates of cloud-top temperature and visible optical depth on spatial scales of tens of kilometers. These data have seen only limited use in climate model validation (e.g., Klein and Jakob 1999; Webb et al., 2001). More of this kind of analysis is needed. In addition, more detailed global observations of clouds, including such things as vertical structure and cloud particle size, are needed to test climate model parameterizations and their relationship with precipitation, water vapor, and air temperature.

Current satellite data give only rather crude estimates of cloud particle size and cannot readily distinguish cloud water from cloud ice. Passive infrared sensing of cloud-top height is imprecise when the clouds are not optically thick, which is an important constraint when studying high, thin clouds in the tropics and elsewhere. New cloud data are becoming available from instruments on satellites that use polarization of reflected sunlight and active scanning with cloud radars and lidars to probe the vertical structure and particle size of clouds. These data will provide an important new source of data on the global distribution of clouds that should be used to further constrain and test the simulation of clouds in climate models.

Incomplete Theories

Climate feedback hypotheses are necessarily concerned with large, complex, and coupled systems that do not necessarily obey simple laws. Most simplified feedback "theories" involving clouds consider only a limited set of the critical processes, even though the neglected processes are known to be important. For example, the thermostat hypothesis (Ramanathan and Collins, 1991) argues that the sensitivity of tropical convective cloud albedo will constrain tropical sea surface temperature (SST) below 303K. But the analysis implicitly assumes that spatial variations of clouds and SST are a useful analogy for climate change, when in fact they are not (Hartmann and Michelsen, 1993; Lau et al., 1994; Wallace, 1992). And, the Iris hypothesis (Lindzen et al., 2001) speculates that the area of tropical anvil clouds will decrease with increasing SST, but again the observational evidence uses a gradient with latitude as an analogy for climate change, which it is probably not (Hartmann and Michelsen, 2002). Simple theories for how clouds will respond to global warming are difficult to test using observations, since only a small global warming has so far been observed. It is easier to test the response to large forcings, such as the annual and diurnal cycle, which are well observed and the response amplitude is large.

The treatment of clouds in climate models is still highly simplified, although current climate models are including more of the relevant physics of cloud processes. New data to validate these models is becoming available from measurement programs such as DOE's Atmospheric Radiation Measurement (ARM) program and new satellite observations. In most models, however, the key linkages between processes are often broken. For example, the separation of parameterized convection from large-scale cloudiness effectively decouples clouds from the model hydrological cycle. This artificial separation creates problems when attempting to use models to advance understanding on cloud and water vapor feedbacks. Additional problems with cloud schemes in climate models include

- the introduction of model resolution dependence to the parameterizations of clouds. For example, the cloud processes represented by the large-scale schemes are typically microphysical in nature. The parameters that represent these processes have to be heavily tuned to the scale resolved by the model. This introduces an unavoidable degree of arbitrariness to the cloud feedback problem since global-scale cloud observations of these processes needed for tuning are lacking.
- a growing confusion between those processes that are really represented by the sub-grid-scale schemes and those processes that are represented by the resolved scales. This in turn creates a further degree of arbitrariness as to how to use existing observations (of precipitation, for example) to assess the merits of different parameterizations.
- cloud feedbacks currently addressed in global scale models chiefly articulated in terms of the resolved cloudiness and thus chiefly in terms of cloud radiation interactions. When averaged over time, the global energy balance of the atmosphere is fundamentally between latent heating

associated with precipitation and the radiative heating, and notably including the contribution by clouds on the radiative heating (e.g., Stephens et al., 1994), so that latent heat release and radiative heating must be closely linked. The observed diurnal variation of convective precipitation is a manifestation of the interplay between radiation and convection. It is difficult to treat this kind of interaction in existing global models that deal with precipitation and related processes (by sub-grid-scale convection) in isolation from clouds and their radiative heating.

Untested Predictions

In general, quantitative tests of the role of clouds in global climate change are difficult to devise since one cannot observe a climate change. The best that can be done is to use a long record of climate, including cloud information, and test the models ability to simulate the observed variability. Such model evaluations require comparison datasets of relevant information accumulated over extended periods of time. Developing long-term datasets of even rudimentary parameters, let alone cloud parameters, has proven to be difficult for a number of reasons, including the lack of dedicated global monitoring and observing systems for this purpose (NRC, 1999a). Despite these difficulties a number of valuable global datasets have been compiled over the past two decades. That these datasets are underutilized is in part a reflection of the attention that has been paid to model intercomparison, but too little attention has been paid to testing models against data. The utility of model-to-model intercomparison exercises for characterizing and reducing uncertainty in climate change feedbacks is limited. Without rigorous and multifaceted comparisons of models to as much data as possible, model intercomparison activities tend to make the feedback processes behave similarly to one another while generating no evidence that their consensus behavior is any nearer to that of nature.

DEVELOPING A SCIENTIFIC STRATEGY

Despite the challenges described above, the potential for making important strides in understanding is very high at the present time, for the following reasons.

Improved Global-Scale Experimental Data

In the most sophisticated cloud-resolving models (CRMs), NWP models, and climate models, the clouds are currently predicted in terms of three-dimensional distributions of cloud water and ice, using conservation equations for these quantities, so that fully prognostic cloud simulations have become the norm. The ability of these models to simulate the three-dimensional fields of water and ice correctly cannot be adequately tested at the present time because of a lack of sufficiently detailed global data, thereby thwarting model assessment and subsequent improvement. Datasets from satellite- and ground-based observations are currently being developed that would enable the validation of these more sophisticated models, if a sufficient effort is made to do so. Examples of datasets include cloud and aerosol data from Earth Observing System (EOS) instruments and cloud vertical structure data from the Cloudsat satellite. Surface data from the ARM provide a new capability to measure critical cloud properties at selected locations (Mather et al., 1998; Stokes and Schwartz, 1994). The availability of global-scale data on precipitation, albeit confined to the global tropics (Kummerow et al., 2000), as well as the near-future availability of global cloud water and ice information from other planned satellite measurements (Stephens et al., 2002), provides the much needed datasets for evaluating cloud predictions under a variety of weather regimes.

Evaluating Model Predictions

Running models in a forecast mode is one way the link between heating and circulation can be examined, at least in the context of testing the shorter-time-scale feedbacks. Comparisons of the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP predictions of cloud cover and occurrence, albeit limited in scope, show an encouraging degree of agreement with existing data (Hogan et al., 2001; Klein and Jakob, 1999; Miller et al., 1999). These comparisons go beyond superficial comparisons of areal cloud amount by examining the vitally important vertical structure. Still missing are diagnostic studies of cloud property information such as liquid and solid water contents with corresponding quantitative precipitation. Information from CloudSat could help fill some of these observational gaps (Stephens et al., 2002).

Studies such as these highlight the utility of being able to run climate models in an NWP mode to perform diagnostic analyses of processes that operate on short time scales but that are critical to producing realistic projections of long-term climate change. With increasing computation power expected in the coming years and the higher spatial resolution expected of these global models, continued improvements in the representation of smaller-scale cloud processes with the subsequent improvement in predictions of cloud properties is anticipated. Thus, with improved resolution and improved global observations noted above, more probing testing of model parameterizations is possible, which is expected to lead to better parameterization methods and better cloud predictions. If adequately supported, the GEWEX Cloud Systems Study (Randall et al., 2000), which is focused on developing improved parameterizations for a wide variety of cloud types, is expected to contribute substantially to this effort. The approach generally combines observations, cloud-resolving models and global climate models.

Better cloud predictions in turn will lead to more capable assimilation methods eventually expanding the use of existing and archived data, such as the archived but unused cloudy-sky radiance data derived from operational analyses. This then should feed back on model development with subsequent improvements. Validated cloud predictions should also expand diagnostic uses of new re-analyzed data expected from future re-analysis efforts that could be an integral part of the cycle of model evaluation, improvement, and data analyses.

Toward Improved Theories

Cloud-resolving models (CRMs) have evolved as one of the main tools for studying the links between key processes pertinent to studying cloud-related feedbacks (e.g., Browning, 1993; Grabowski, 2000). As such, these models may be viewed as an essential tool for articulating the underlying theories of cloud feedbacks. These models continue to improve and are now being adopted more widely in a variety of cloud and precipitation research activities. CRMs are also being coupled experimentally ways into global models to serve as an explicit form of cloud parameterization, thereby overcoming the problematic separation between resolved cloudiness and unresolved convection (Randall et al., in press).

CRMs embedded within GCMs should not be viewed as a panacea because they do not actually simulate the complete cloud dynamics in a GCM grid cell; rather, they provide a physical representation of the cloud statistics in the cell. They are also quite computationally intensive to run in this way. Moreover, it remains to be seen how difficult it is to develop a cloud resolving GCM with realistic sensitivity of global mean surface temperature.

Despite improvements and increasing use of CRMs, their evaluation is far from extensive, being limited to a few test cases from a limited number of field campaigns. Future testing must examine the sensitivity of CRM simulations to assumptions in their microphysics and turbulence parameterizations and the limitations this sensitivity may impose. The cloud evolution predicted by these models is also sensitive to initial conditions (including the large-scale forcing that drives them). This sensitivity is problematic given that the source of this forcing usually derives from the analyses of large-scale operational models. Therefore, progress in CRMs has to be intimately tied to progress in NWP global models. Mutual improvements in turn can be expected to lead not only to better cloud prediction schemes in global models but also can be expected to promote new assimilation methods applied to CRMs and eventually a more penetrating way of testing and improving models with observations. These caveats should not overshadow the potential that CRMs present as tools to explore the interaction between the cloud physics and the general circulation of the atmosphere

The cloud feedback problem and the indirect effect of aerosols are linked together. The provision of aerosols is hypothesized to affect the water budget of clouds through the indirect effect. But this affect cannot be understood without understanding the effects of dynamics and thermodynamics in providing moisture for clouds. In most cases one would expect the circulation and thermodynamics to have a much larger effect on the cloud properties than the provision of additional aerosols. Therefore one can argue that a good understanding of the relationship of cloud properties to the dynamics and large-scale thermodynamic environment of the clouds is necessary before the effect of additional aerosols can be convincingly predicted. To resolve these issues will probably require testing when the aerosol abundance is known as well as the dynamic and thermodynamic conditions. The effect of the dynamic and thermodynamic environment can then be separated from the aerosol effect and solved first. Direct measurements of aerosols and associated cloud properties may also provide critical information (Bréon et al., 2002; Lohmann and Lesins, 2002).

Progress in understanding cloud, water vapor, and lapse rate feedbacks requires that an integrated effort with additional resources be developed that cross-cuts the interests of individual agencies. We propose that this effort be developed with the following elements:

- **Improving Datasets and Data Analyses.** The fundamental problem is that the scientific community's efforts to model the basic physics of cloud, water vapor, and lapse rate feedbacks are much more advanced than the ability to measure the nature and evaluate the accuracy of their simulation in climate models. Therefore, a vigorous strategy should be implemented to promote and fund research that

  –maintains the important global datasets already under development but in jeopardy due to lack of support (e.g., GEWEX-related datasets such as the ISCCP and the Global Precipitation Climatology Project [GPCP]);
  –uses existing datasets specifically to evaluate cloud, water vapor, and precipitation predictions in global-scale weather and climate models, as well as regional-scale cloud-resolving models. A focus should be placed on developing rigorous diagnostics methods and evaluation procedures; and
  –extends these activities to embrace the new improved datasets expected in the coming years.

- **Testing predictions.** A rigorous effort to test climate models against observational metrics must be initiated and coordinated among groups performing climate modeling, climate observation, and climate analysis. Metrics should include comparison of observed and simulated response of clouds, water vapor, and lapse rate to every well-observed forcing mechanism and time scale, including the diurnal and seasonal response, the response to ENSO and the response to volcanic eruptions. This intercomparison should include the estimation of global feedback parameters from seasonal variations (e.g., Tsushima and Manabe, 2001) and regional feedbacks as understanding warrants.

Additional metrics should include cloud and water vapor variations associated with day-to-day weather changes. Weather prediction models and connected assimilation systems should be applied to the diagnosis of critical links between cloudiness, water vapor, precipitation, and weather variations. Within this effort, new methods for the assimilation of cloud, water vapor, and precipitation data must be promoted. Therefore, ongoing attempts to coordinate national climate modeling efforts must include an NWP component with data assimilation as well as a data assimilation effort using climate models. The time scales of relevance include diurnal, weekly (characteristic of weather systems), seasonal (characteristic of natural modes of variability; see Chapter 9), and decadal (characteristic of long-term climate change).

- **Improving theory and models.** A significant effort should be undertaken that builds upon the preceeding two elements with the specific goal of improving the representation of clouds, water vapor, and precipitation in NWP and climate models. This activity should use an integrated, hierarchical approach to model development connecting NWP model and assimilation developments, climate model parameterization developments, and cloud-resolving models. This effort must go significantly beyond the current model intercomparison projects, which have played an important role in identifying model errors and in developing uniform model diagnostics, but frequently have lacked an observational underpinning.

The potential of this approach will not be realized without a more coordinated program of research and support. Progress on atmospheric hydrology feedbacks has been hindered by fragmented resources, which discourages crosscutting research in modeling, observational techniques, and diagnostic analyses. For example, research in collection and analysis of the global datasets of cloud and water vapor information, especially those derived from space-borne observations, are supported in large part by NASA, the development of NWP models by the National Oceanic and Atmospheric Administration (NOAA), and high-end climate modeling efforts by yet other agencies, each of which have their own objectives. A viable strategy for progress requires a thoughtful, efficient integration of observations, diagnostic research, global model development, data assimilation, and cloud-scale modeling. These elements have to be connected in one program as progress on any specific element of this strategy depends on progress on connected elements.

3

SEA-ICE FEEDBACKS

SUMMARY

Ice and snow in high latitudes, and in particular sea ice, contribute importantly to climate sensitivity through ice-albedo feedback, but the magnitude of this feedback remains uncertain. Ice-albedo feedback in polar regions is coupled strongly to polar cloud processes and ocean heat transport. Better monitoring of polar ice distributions and associated atmospheric and oceanic properties is needed. Systematic global observations of sea-ice thickness are needed, but a system to make these measurements is unavailable. Improvements are needed in the parameterization of sea-ice growth, associated heat and freshwater fluxes, the variable surface albedo, and polar clouds.

Parameterizations of snow and ice processes in climate models and their effect on climate sensitivity need to be tested against observations using an appropriate set of metrics. Further development and distribution of satellite and in situ datasets describing variations of polar ice and polar clouds should be a priority.

Various positive feedbacks and other important linkages between the atmosphere and Earth’s surface occur through sea-ice processes, which themselves are subject to conditions in the ocean’s surface layer. At high latitudes when the ocean surface temperature drops to about -1.8°C, sea ice forms on the ocean surface. Ice has a strong impact on climate because the associated feedbacks are positive and large. The presence of sea ice both insulates air-sea heat exchange and increases the surface albedo, thereby affecting climate through a reduction in oceanic sensible and latent heat loss to the atmosphere, and reducing the amount of absorbed incoming solar radiation, respectively. Albedo effects are also linked with cloud radiation balances in ice-covered regions. Ice insulation has a weaker direct effect on climate since sensitivity to ocean surface temperatures is low in high latitudes, but indirectly the impact could be large since ice extent partially depends on underlying ocean conditions. In addition, sea ice represents a source of freshwater that through advection from one location to another can affect the properties of deep and intermediate water formation in the ocean.

Sea ice is a highly responsive component of the global climate system due to its high albedo and its participation in the hydrologic cycle. The IPCC TAR identified the coupling between sea ice and atmosphere and between sea ice and ocean to be of great importance in defining the sensitivity of the global system. Important sensitivities include the feedback between surface albedo and ice extent and properties; the ice-insulating effect; and the relationship between the North Atlantic thermohaline circulation and sea-ice export through Fram Strait.

Of these the albedo feedback is the greatest influence. A perturbation to the surface energy balance of the sea ice results in a perturbation to ice area, surface temperature, melt pond and lead fraction, snow depth, ice thickness and other sea-ice characteristics. A positive (warming) perturbation will lead to an increase in the amount of solar radiation that is absorbed by the planet. Thus, increases in the temperature cause increases in the amount of solar radiation absorbed by the surface, leading to further increases in temperature. This association of temperature, ice cover and characteristics, and albedo is called ice-albedo feedback. Ice albedo feedback is a positive feedback process in that it amplifies the temperature response to climate forcing. However, until our physical understanding of the component processes is improved, the interdependence among these processes remains unquantified.

The magnitude and even the sign of some of the other polar feedback processes are also associated with significant uncertainties. Much of this uncertainty is related to cloud radiation feedbacks and how polar cloud characteristics will be altered in a changing climate. Because of the impact of clouds on the surface radiation flux and thus the state of the sea-ice surface, the cloud radiation feedback processes in the polar regions are inextricably linked with sea ice and snow feedback processes. Our best estimate at present is that all of the individual cloud, snow, and sea-ice feedbacks in the polar regions are positive, with the exception of the aerosol-dehydration feedback. It remains a major task in climate modeling to explain the relative stability of the polar climate in the presence of these positive feedbacks. Possibilities include unexpected negative cloud feedbacks, or negative feedbacks between the sea ice and ocean.

Outlined below are some of the potentially most important polar feedbacks. These feedbacks should not be viewed as mutually independent, but rather as interconnected components of a complex system.

OVERVIEW OF SEA-ICE FEEDBACKS

Ice-Albedo Feedback

Warming of high latitudes can decrease the areal extent of sea ice, especially in the summer, leading to a decrease in surface albedo and an increase in the absorption of solar radiation at Earth's surface, which would favor further warming. In model studies the magnitude of the positive ice-albedo feedback has been seen to increase by the inclusion of melt ponds, and to diminish by the inclusion of ice thickness distribution and ridging.

Ice Insulating Feedback

Warming of high latitudes decreases the areal extent of sea ice, especially in the summer, providing an enhancement to the warming through removing the insulating effect of sea ice on air-sea heat exchange (Manabe and Stouffer, 1980).

Meridional Overturning Circulation and SST-Sea-Ice Feedback

While the actual future path of the Atlantic meridional overturning circulation (MOC) is not known, it is possible that in the short term the ocean could act as a negative feedback to high-latitude warming (Bryan, et al. 1988; Gent, 2001). The role of deep ocean heat in the Antarctic subpolar gyres (delivered by the MOC) plays a critical role in regulating the thickness of the insulating Antarctic sea-ice cover (Martinson, 1990). Consequently, one may assume that any change in the MOC may result in a change in this deep ocean heat content and thus the sea-ice thickness. The latter will impact the length of the sea-ice season, insulating effectiveness, freshwater transport by sea-ice drift, and deep and intermediate water formation (feeding back into the MOC directly). It is difficult to predict the nature of the sign of the net feedback, since we need a better understanding of how changes in the MOC may impact the properties of the subpolar deepwaters.

The net change will depend upon the balance of a variety of detailed local air-sea-ice exchange processes, and this is difficult to estimate in typical low-resolution climate models.

Ice–Cloud Feedback Processes

Because of the impact of clouds on the surface radiation flux and thus the state of the sea-ice surface, cloud radiation feedback processes in the Arctic are inextricably linked with albedo feedback processes. A perturbation in the surface radiation balance of the snow or ice, which could be produced by input of greenhouse gases and aerosols, results in a change in snow or ice characteristics (i.e., ice thickness and areal distribution, surface temperature, and surface albedo). These changes in surface characteristics, particularly the surface temperature and fraction of open water, will modify fluxes of radiation and surface sensible and latent heat, which will modify the atmospheric temperature, humidity, and dynamics. Modifications to the atmospheric thermodynamic and dynamic structure will modify cloud properties (e.g., cloud fraction, cloud optical depth), which will in turn modify the radiative fluxes.

DEVELOPING A SCIENTIFIC STRATEGY

The polar climate community is poised to make rapid progress in these areas. In particular the United States is uniquely positioned to improve our understanding of these feedbacks, because many of the relevant satellite datasets are being developed in the United States, and some of the relevant modeling activity is concentrated here as well.

Many of the assembled datasets are already in place, or field campaigns are planned that will address deficiencies in in situ data requirements. The one caveat to this assessment is the paucity of ice thickness data over large space and time scales. There remain serious technological difficulties in making extensive observations of this type. It may require further development of upward-looking sonar (ULS) technology before reliable collection will be possible.

Two of the other potential impediments to progress are insufficient data-processing and archival facilities and inadequate funding for creating detailed climate-quality satellite datasets (e.g., NRC, 2000b) over longer time periods. Another point worth noting is that most current funding addresses specific science questions. We view this favorably. However, insufficient funding has been available for developing the necessary new monitoring technologies, large datasets, and comprehensive models.

Specific strategies for characterizing and reducing the uncertainty in polar feedbacks need to consider not just cloud processes and sea-ice processes but linkages between them and the relationships between these processes and interannual variability.

Observations

The most comprehensive source of sea-ice data of large space and time scales is satellite-derived data, which includes sea-ice concentration, snow extent and ice motion from passive microwave data, sea-ice concentration from MODIS and leads from the Advanced Very High Resolution Radiometer (AVHRR). Some ice thickness data may become available from Icesat (Zwally et al. 2002). Less extensive data from, for example, the Arctic and Antarctic Drifting Buoy programs and ice draft from ULS add in situ data.

In addition, an unprecedented Arctic sea-ice dataset is being assembled under the auspices of the U.S. Surface Heat Budget of the Arctic Ocean (SHEBA) project (Uttal et al., 2002). High-quality surface data is available at the SHEBA ice camp in the Beaufort and Chukchi seas; aircraft observations were made during a four-month period in a region over the Beaufort and Chukchi seas, and several satellite remote-sensing groups are focusing on the SHEBA field season of October 1997 to October 1998. Several remotely sensed datasets will be made available on a basin-scale for this project. These data should be fully utilized to advance understanding and improve model parameterizations.

Although not directly related to ice, an understanding and correct simulation of the cloud radiation feedback in polar regions requires observations of (1) cloud fractional coverage and vertical distribution as the vertical temperature and humidity profiles change, and (2) changes in cloud water content, phase, and particle size as atmospheric temperature and composition changes. The largest uncertainty in assessing the cloud-climate feedback mechanism is the change in cloud cover in response to a change in atmospheric temperature. Even the sign of the cloud-climate feedback over the Arctic is unknown. Cloud radiation feedbacks and the required observations are also discussed in Chapter 3.

Because of the different thermodynamic and radiative environment in the polar regions, conclusions drawn for the globe regarding these feedback processes may be inappropriate over the Arctic and Antarctic. Detailed satellite datasets must be extended to include Antarctic products at the same level of detail as for the Arctic. In addition, the record length of detailed satellite datasets must be extended to account for interannual variability and characterization of ice thickness must be extended in time and space.

To advance understanding and thereby possibly reduce uncertainty about important cryospheric feedback processes, the committee recommends that *detailed satellite datasets must be extended to include Antarctic products at the same level of detail as for the Arctic. In addition, detailed satellite datasets must be extended in time and space to account for interannual variability and characterization of ice thickness.*

The ability of climate models to simulate the observed annual cycle of sea-ice extent, thickness, and concentration should be carefully tested. In addition, the interannual variations of these quantities in free-running climate models should be compared against observations.

Modeling

The state of the art in sea-ice modeling is fairly advanced relative to what is currently being used in most state-of-the-art climate models. Most if not all major coupled climate models have crude representations of sea-ice physics. Some models still use a purely thermodynamic treatment of sea ice and others often only incorporate crude representations of sea-ice dynamics (e.g., cavitating fluid, free drift). Climate models show strong sensitivity to sea-ice representations (Holland et al., 2001; Liu et al., 2003). It is difficult to assess the importance of sea-ice-climate feedbacks without coupling sea-ice models to prognostic ocean and atmosphere models. It can be argued that on large scales, the use of current, state-of-the-art parameterizations of ice dynamics and correct atmospheric dynamical forcing will lead to reasonable simulations of ice extent, if the ice thermodynamics is well represented. Local thermodynamic processes (even over multiyear ice) and exchange with the atmosphere influence surface type and hence albedo. The detailed exchanges of heat and freshwater with the atmosphere and ocean are processes that disciplinary modelers (ice, ocean and atmosphere) often neglect. These interfacial processes are crucial to an understanding of sea-ice feedbacks.

Taken together the uncertainties outlined in Chapter 3 on water vapor and cloud feedbacks highlight several areas of priority where substantial and rapid scientific advances can be made in the areas of process parameterization and model development, especially in light of improved and expanded datasets.

In the area of sea-ice feedbacks our general modeling recommendations are the following. *Initiatives should be developed to improve the parameterization of new sea-ice growth and its associated heat and freshwater fluxes, snow over sea ice (especially the surface temperature) and surface albedo that responds to surface ice characteristics, including melt ponds. In addition, parameterizations are urgently needed for the unique properties of Arctic and Antarctic clouds. We also recommend that major U.S. modeling groups incorporate and rigorously test more sophisticated treatments of sea ice and related parameterizations in coupled models.*

4

OCEAN HEAT UPTAKE AND OCEAN CIRCULATION FEEDBACKS

SUMMARY

The rate of global warming and the spatial distribution of warming are influenced by the uptake of heat by the oceans. Sea surface temperature (SST) is set by the ocean's heat uptake from the atmosphere; upper ocean stratification, which depends on temperature, salinity, and winds; and ocean currents, which are driven by the atmosphere. The SST is in turn a surface boundary condition for the atmosphere, impacting large-scale atmospheric wind patterns, most directly in the tropics, and impacting storm tracks and intensity at mid-latitudes. Ocean surface temperatures also impact ice cover at high latitudes and thus influence albedo, which influences the atmosphere and hence the ocean temperatures. Poor knowledge of all these processes and consequently their parameterizations in climate models contribute to widely varying climate model projections.

To better represent the exchange of heat and carbon dioxide at the air-sea interface, physical representations of upper ocean processes need to be improved in climate models based on experimental studies of the vertical structure of temperature, salinity, and absorption of solar radiation representative of different ocean environments, including high northern and southern latitudes. Improved definition of the time-dependent temperature and salinity distribution in the global ocean is essential, including the air-sea fluxes of heat and freshwater. This will require full implementation of a system with the capabilities of the current and planned ocean-observing satellites, the Argo global array of profiling floats, the in situ tropical ocean observation networks, and a strategy for monitoring key regions of the ocean where deep-water formation important for the thermohaline circulation occurs, such as in the Labrador, Greenland-Iceland-Norwegian, Weddell, and Ross seas.

The enormous volume and thermal inertia of the ocean moderate the daily, seasonal, and interannual temperature fluctuations. The ocean also acts as a large-scale conveyor of heat from low to high latitudes in response to differential heat and freshwater exchange with the atmosphere. The ocean is a vast reservoir of carbon dioxide, thereby providing both a potential source and sink of this radiatively important greenhouse gas.

As the climate is warmed by human activities the processes that regulate heat uptake in the ocean will have a strong influence on the rate of warming (Wiebe and Weaver, 1999). As the winds and the difference between precipitation and evaporation change in a warming climate, the processes that determine ocean surface temperature, particularly in the tropics, will strongly influence the regional responses around the globe to the warming, and may also influence the rate of warming (Manabe et al., 1990). The evolving surface temperature will in turn affect the winds and sea ice. If the effects of a warmed climate weaken the overturning of the ocean at middle and high latitudes, the warming will proceed more rapidly, and large regional shifts in climate may occur.

The discussion in this chapter deals primarily with the role of the ocean in feeding back on anthropogenic climate change. Ocean heat uptake is also discussed here with regard to the role it plays in projections of future climate change. We recognize that strictly speaking the latter subject matter is outside the scope of this report on feedbacks; however, due to the scientifically inseparable nature of ocean heat uptake and climate change feedbacks and the importance of heat uptake for projecting future climate change, we have included both here.

Coupling and feedback between ocean processes and the atmosphere involves the ocean's dynamical state, including overturning, mixing, and stratification in the ocean's surface layer, as well as movement of heat and freshwater from one region to another, horizontally and vertically, mainly driven by the winds. Significant portions of even the thermohaline (conveyor) circulation are wind-forced, through advection and upwelling in the upper ocean. To the extent that the atmosphere is sensitive to ocean conditions, the winds are then affected and in turn force the ocean, the necessary ingredients for feedback. For example, changes in the strength of the Arctic oscillation may affect the strength of the overturning, which could in turn feed back on the strength of the Arctic oscillation.

Direct atmospheric sensitivity to the oceans is generally strongest in the tropics. At higher latitudes sea-ice cover and hence albedo is an important factor, and thus climate is indirectly sensitive to ocean conditions affecting sea ice at these latitudes. But the overall ocean's surface temperature is a function of the ocean's heat capacity, upper ocean salinity stratification, and large-scale advection patterns. Major dislocations of SST, such as those that occur during large climate changes, have an effect on the atmosphere and its dynamics.

The ocean's impact on the atmosphere and hence climate is through SST, which affects the overlying atmosphere's heat content, winds, storms, and water vapor content, and through its role in biogeochemical cycles (see Chapter 8). The best-known and possibly strongest climate feedback involving the ocean is the El Niño-Southern Oscillation (ENSO), which is centered in the equatorial Pacific and produces a strong interannual climate variation that impacts a large portion of the globe. ENSO and its modulation through additional physical processes (discussed in Chapter 9), as well as other natural modes of variability are outlined in Chapter 9. Feedbacks associated with sea ice were described in Chapter 4. Here we single out feedbacks that involve mixing, local air-sea fluxes, and thermohaline (deep ocean) circulation processes.

MIXING, OCEAN HEAT UPTAKE, AND CLIMATE FEEDBACKS

To understand the transient nature of ocean heat and carbon uptake and how they affect atmospheric SST and carbon dioxide (CO_2) levels, one must consider the processes whereby heat and carbon are exchanged at the surface and whereby these changes are communicated between the surface and the deeper layers of the ocean. The exchanges of freshwater at the surface through evaporation, precipitation, and freezing are also critical for setting the density structure of the ocean at its surface. Mixing processes communicate the effects of surface freshwater fluxes into the deeper ocean, where they affect the density-driven circulation.

Exchanges at the Surface of the Ocean

The interface between the atmosphere and ocean is critical for coupling and feedbacks that involve both systems. The transfers of heat, moisture, momentum, and carbon across the air-sea interface are crucial in determining the potential for ocean heat uptake and circulations to feed back on climate change. Better understanding of the physics of exchanges at the air-sea interface is needed. This requires observational and process-oriented research efforts designed to better characterize and reduce uncertainties in both the observation and parameterization of air-sea fluxes and the physics of boundary layer transfer. Another overarching issue is that better estimates of observed fluxes of heat and moisture over the oceans are needed so that they can be used as metrics to evaluate the performance of climate models.

Oceanic Mixed-Layer Processes

Conditions in the ocean mixed layer directly affect the atmosphere, while atmospheric forcing is communicated to the ocean through the mixed layer. The mixed layer is also important for its influence on ice formation. Surface waves and associated surface turbulence are the main interface for ocean-atmosphere gas and momentum exchange, and for injection of some aerosols into the atmosphere. Sea state (wave conditions) depends on wind speed. As winds increase, sea state increases and air-sea exchange accelerates. Wind speed and sea state also affect the ocean's evaporation rate, and hence heat exchange between the ocean and atmosphere. These turbulent exchanges are usually parameterized with bulk coefficients multiplying the relevant parameter such as wind speed or humidity, rather than relying on detailed prediction or observation of the waves themselves. SSTs are an integral part of this system. They not only affect the atmosphere through their influence on heat exchange but the horizontal gradients of SST also affect the strength of winds. An example is the trade wind response to changes in tropical Pacific SST gradients.

Surface layer mixing is driven by turbulence associated with wind speed and by convection due to surface cooling. Mixed layer depth and properties also depend on the density difference between the mixed layer and underlying water. Both temperature and salinity stratification are important. Salinity stratification was often ignored in the past in the search for simplified solutions, but in the 1990s it became widely recognized that salinity is the dominant factor in near-surface stratification in the tropics and in subpolar and high-latitude regions (i.e. in regions with excess precipitation and runoff).

The ocean absorbs incoming solar radiation over a depth that sometimes exceeds the mixed layer depth. This absorption warms the water column. Absorption depends on how clear the water is. In the presence of large sediment loads or large biological productivity, absorption is limited to shallower depths and SST can be significantly higher (3-4°C) (Denman, 1973; Martin, 1985). The vertical distribution of absorption affects upper layer stratification, thereby influencing mixed layer dynamics and SST. If absorption is shallower and SST is increased, upper layer stratification increases, thus furthering the SST increase. Higher temperature may also increase biological productivity, which also produces a positive feedback.

Modeling of surface layer processes should be improved through incorporation of information from focused observational activities. Sustained observations at a number of locations that represent the variety of ocean conditions should involve air-sea fluxes of heat and freshwater, upper ocean temperature and salinity structure, and absorption of solar radiation. These observations must be conducted in several regions (including high northern and southern latitudes) representative of different ocean environments. The seasonal and sub-seasonal variations in these profiles and in the measurements of the upper ocean from expendable bathythermographs (XBTs), the Argo array of profiling floats, the Tropical Ocean Global Atmosphere program's Tropical Atmosphere Ocean project (TOGA/TAO), the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), undersea gliders, and a combination of satellite measurements of sea surface height and ocean color can be used as metrics to test understanding of the uptake of heat by the ocean and their simulation in climate models.

Some of the important variables for this are large-scale sea surface height and temperature, upper ocean heat content, and pycnocline depth patterns in the North Pacific, in the North Atlantic, and in the mid-latitude Southern Ocean. These can be used to measure and diagnose the circulation strength and phase of natural decadal time-scale modes, including the Arctic (North Atlantic) and Antarctic oscillations and the Pacific decadal mode. Changes in the strength or phase of these natural modes are likely to occur with anthropogenic forcing.

Interior Ocean Diffusivity Changes

Interior ocean mixing is very important for determining the rate of uptake of heat and carbon. Observational evidence suggests that diapycnal diffusivity (i.e., across levels of equal density known as isopycnals) is a strong function of location. Along isopycnal (i.e., nearly horizontal) diffusivity is also sometimes modeled as a function of location, depending on the strength and hence instability of currents. If current strengths decrease in response to climate warming, mesoscale energy also decreases, providing less mixing along isopcynals. This could increase SST gradients, which would provide a feedback, likely negative, increasing winds and thus increasing current strengths.

Diapycnal diffusivity is due to interior turbulence, mainly caused by internal waves. Internal waves are forced by tides and by the wind. The connections between tides, winds, internal waves and diffusivity are being examined now through intensive in situ experiments. Diapycnal diffusivity is high in the surface layer where winds have a direct effect. Here mixing is enhanced with strong winds, with potential feedbacks as described above.

Recent observations also show that diapycnal diffusivity is high near the ocean's solid boundaries, and is especially high where topography is rough. It is not yet clear whether long-period variations in, say, tidal amplitudes, could be amplified enough to produce climatically significant variations in diapycnal diffusivity, although there are some proponents of this idea.

Ocean Circulation and Parameterization of Diffusivity in Simplified Ocean Models

The ocean models used in climate modeling are sometimes extremely simplified in order to test parameter ranges and scenarios for phenomena that do not depend strongly on the ocean. These simplified ocean models usually have very coarse resolution and hence are very viscous. They cannot provide insight for feedbacks that actively involve the ocean. The central issues for these simplified ocean models are their absorption and advection of heat and accurate representation of SST.

Many modeling studies have shown a strong dependence of the climate response to radiative forcing on the parameterization of sub-grid-scale ocean mixing (see Griffies et al. [2000] for a review). It is clear that there is an urgent need for improved parameterizations of ocean mixing that account for the observed spatial inhomogeneity of both diapycnal and isopycnal ocean mixing. These improvements should be developed through theoretical work coordinated with ongoing observational programs and field studies. To reduce dependence on sub-grid-scale parameterization, climate-modeling groups should continue moving toward improving both the resolution and physics of the ocean in climate models used to make future projections of climate change.

THERMOHALINE CIRCULATION FEEDBACKS

The thermohaline circulation is defined as the component of the ocean circulation driven by fluxes of heat and fresh water through the ocean surface. In the present climate the North Atlantic and Southern oceans are the two regions of deepwater formation where warmer surface waters are converted to colder deepwaters through intense heat loss to the atmosphere. In the North Atlantic high-latitude cooling together with low-latitude heating accelerates the thermohaline circulation (Atlantic meridional overturning circulation [MOC]) with poleward flow at the surface. On the other hand net high-latitude precipitation, runoff, and ice melt and mid-latitude evaporation tend to oppose the thermally driven thermohaline circulation. The deepwater formation sites are localized in the Greenland and Labrador seas, hence the recommendations in this report for monitoring these sites and their outflows. The northward flow of warm upper ocean water with southward flow of cold deepwater provides most or all of the northward ocean heat transport in the Atlantic (Roemmich and Wunsch, 1985). This northward heat transport extends much farther north than in the North Pacific, which has no deepwater formation and where northward heat transport is associated with shallow overturn only (Talley, 1999).

Climate feedbacks associated with the Atlantic MOC involve this northward transport of warm water, which reduces the equator-to-pole temperature gradient in the North Atlantic. If the Atlantic MOC strength were reduced through a reduction in high-latitude cooling and/or increase in high latitude freshwater, upper ocean and hence atmospheric temperatures in the northern regions would decrease. A concomitant increase in temperatures might occur in the South Atlantic (Broecker, 1998; Stocker, 1998).

The possibility of an abrupt change in the Atlantic MOC in response to increases in greenhouse gas concentrations has been demonstrated in a number of simulations with models of the coupled ocean-atmosphere system (NRC, 2002). The inherent nonlinearity of such an abrupt event, together with the sensitivity of the behavior on poorly constrained parameterizations of ocean mixing (Schmittner and Weaver, 2001), makes it extremely difficult if not impossible to assign a probability for the future occurrence of abrupt climate change over the next century. See the NRC report on *Abrupt Climate Change* (NRC, 2002) for an extensive discussion of this issue.

Much less is known about the meridional overturning in the Southern Ocean, not because of its lack of importance but rather due to the harsh environmental conditions and lack of nearby populated continental landmasses. The Southern Ocean meridional overturn has two major components: upwelling of Northern Hemisphere deepwaters all around Antarctica, which feeds subsequent bottom water formation along the continental shelves under the sea ice. Bottom water formation occurs primarily in the Weddell and Ross seas, with additional sites along the coast of Adelie Land. Interactions of the overturning circulation, upwelling, northward Ekman transport, ice edge and albedo, fresh surface layer, and the polar winds involve numerous feedbacks (e.g., Gnanadesikan and Hallberg, 2000; Keeling and Stephens, 2001; Rind et al., 2001; Toggweiler and Samuels, 1993; Thompson and Solomon, 2002). The Southern Ocean is also a major site of carbon exchange between the atmosphere and ocean (Sabine et al., in press; Sarmiento and Gruber, 2002), primarily because of the massive upwelling of deepwaters. The dominant mechanisms equivalent to the Atlantic MOC's impact on long-time-scale climate remains to be determined.

Atlantic Meridional Overturning-SST Feedback

Some modeling studies have noted that over the course of the next few centuries, the Atlantic MOC may move to an off state in response to increasing greenhouse gases (Cubasch et al., 2001). Some, on the other hand, find no such reduction (Gent, 2001; Latif et al., 2000) and others find very little reduction (Cubasch et al., 2001). The reduction in Atlantic MOC strength associated with increasing greenhouse gases leads to a negative feedback to warming in and around the North Atlantic. That is, through reducing the transport of heat from low to high latitudes, SSTs are cooler than they would otherwise be if the Atlantic MOC were left unchanged. As such, warming is reduced over and downstream of the North Atlantic. It is important to note that in all models where the Atlantic MOC weakens, warming still occurs downstream over Europe due to the radiative forcing of increasing greenhouse gases. In different models the competing effects of differential heat and freshwater flux forcing between low and high latitudes fundamentally determine the MOC-SST feedback.

There is some suggestion (Stocker, 1998; Broecker; 1998) that a reduced cross-equatorial heat transport to the North Atlantic with a reduced Atlantic MOC would at quasi-equilibrium lead to enhanced SSTs in the South Atlantic. Thus, a reduction in Atlantic MOC and the stabilization of South Atlantic surface water would suggest a positive feedback to anthropogenic warming in and around the South Atlantic.

Many future projections show that once the radiative forcing is held fixed, reestablishment of the Atlantic MOC occurs at a state similar to that of the present day. During this reestablishment phase the Atlantic MOC acts as a positive feedback to warming in and around the North Atlantic and at equilibrium there is close to zero net feedback. Whether reestablishment of the MOC occurs depends on the parameterization of ocean mixing (Manabe and Stouffer, 1999), as well as the emission rate and eventual stabilization scenario for atmospheric greenhouse gases (Stocker and Schmittner, 1997).

The fundamental MOC-SST feedback is well understood although different models yield different projections in the strength of the MOC over the twenty-first century. This is not because the underlying feedback is unknown but because the feedback is ultimately linked to the air-sea exchanges of heat and freshwater. The basic physics of the latter is still a matter of investigation, and the present observational network needed to constrain the physics and its parameterization in models is far from ideal. The recommendation regarding air-sea exchanges of fresh water in the preceding section is thus critical to better understanding the local feedbacks that might be associated with changes in the Atlantic meridional overturning.

Hydrological Cycle–Meridional Overturning Circulation Feedback

Freshwater export from the Arctic to the North Atlantic Ocean is governed by the total precipitation and runoff into the Arctic. Coupled modeling studies (Cubasch et al., 2001) suggest that a warmer world is one in which the hydrological cycle, and hence runoff into and precipitation over the Arctic, will be enhanced. Freshwater export from the Arctic can either be in the form of sea ice or liquid water and can exit the Arctic into the Atlantic through either Fram Strait or the Canadian archipelago.

All coupled models project an increase in poleward transport of water vapor from low to high latitudes in the atmosphere under enhanced greenhouse conditions. In some this leads to a freshening of the high-latitude North Atlantic, which reduces convection and hence the strength of the MOC. In others no change in the overturning occurs as compensating feedbacks come into play (see discussion of MOC-SST feedback).

Melting of sea ice in the Arctic provides a freshwater source to the North Atlantic, which acts to weaken the conveyor, thereby initiating the Atlantic MOC-SST feedback (see discussion of MOC-SST feedback). Melting of existing sea ice is, of course, a small component of the total change in freshwater export out of the Arctic under enhanced greenhouse conditions. Changes in freshwater export out of the Arctic are controlled by the total atmospheric moisture transport into the Arctic.

The basic understanding of the effects of changes in the hydrological cycle on the MOC is relatively well known. Uncertainty in this area is directly linked to uncertainty in hydrological cycle feedbacks discussed in Chapter 6, as well as uncertainty in the sea-ice feedbacks (see Chapter 4).

Thermohaline Circulation—Wind Feedback

The strength of the wind-driven circulation affects the MOC. In the northern North Atlantic the wind-driven circulation is part of the advection of water northward into the water mass formation areas. Intensification of the low pressure atmospheric system can have several effects: (1) increasing the strength of the subpolar circulation and hence increasing the inflow of lower-latitude waters into convection regions and outflow of lower salinity arctic and subarctic waters to the south, and (2) increasing the heat loss through increased wind speed in the whole subpolar region as well as in the deepest convection regions. The first will reduce surface density throughout the subpolar region, increase density stratification, and could lead to warmer SST where the northward flow is stronger, and colder SST in the low-salinity regions where deep convection is inhibited. The second will increase the propensity for convection and will reduce surface temperatures.

In the Southern Ocean, wind-driven upwelling in and south of the Antarctic Circumpolar Current is an essential part of the MOC. The strength of Southern Hemisphere westerlies can affect the strength of this upwelling and may be the major control on the Southern Hemisphere MOC. Atmospheric warming would not easily disrupt the temperature, although it could affect the net upwelling transport (Toggweiler and Samuels, 1995). A weakened southern polar vortex would be associated with an equatorward shift of the storm track and a reduction in intensity of the cyclonic ocean circulations and upwelling. This might affect the ice edge (reduction in ice cover), which would exacerbate the warming and further weaken the polar vortex. However, because of the deep upwelling the impact of the oceanic portion of this feedback would not be as pronounced as if the upwelling had a much shallower source.

Observations of the Meridional Overturning Circulation

Our current understanding of Atlantic meridional overturning is the product of decades of observations and increased modeling capability. It has been demonstrated that Atlantic MOC processes can effect climate change, particularly in response to large climate forcing, such as occurred at the glacial-interglacial transitions or might occur in response to anthropogenic forcing. As indicated above, much better projection capability will require many more years of in situ process studies and modeling, and long-term monitoring with ongoing predictive modeling. Understanding of the impact of meridional overturning processes in the Southern Ocean is far less advanced. This is likely a reflection of insufficient resources to undertake the necessary studies in this region far away from major oceanographic centers, rather than actual impact of this region on climate. Future observations and modeling of this region are likely to reveal far more of interest to the understanding of long-term climate change than is now known.

One of several metrics that should be employed to advance this understanding and evaluate progress is total water-column heat content along decadally monitored transoceanic cross-sections, especially in the North Atlantic and Southern oceans because of its utility in monitoring the integrated effect of climate forcings and feedbacks. Another set of metrics is the heat and freshwater content at locations with existing long time series that have already been clearly correlated with large-scale climate change and with conditions in the ocean that are implicated in climate feedbacks, including near-coastal regions such as Bermuda. While these specific locations are not in themselves important, the long time series are a proxy for larger-scale ocean conditions that are important in climate change feedback processes. Western boundary current transports and properties, including the Gulf Stream, Kuroshio, Labrador Current, and Oyashio, can be used as indicators of the natural modes (mentioned previously) and in the North Atlantic as the feeder for the deep meridional overturning. Western boundary currents can be observed through a combination of satellite altimetry, moored arrays, and repeat hydrography.

A decade of planning has gone into the far-reaching programs and suites of observations of the international Climate Variability and Predictability (CLIVAR) and the Global Ocean Observing System (GOOS) programs. It would be an error to recommend large programs beyond these fully planned, complex, far-reaching programs. Therefore, our recommendation is that the United States support the ocean process studies being planned by the CLIVAR program in the Atlantic and Southern Oceans, the GOOS program, and the Global Ocean Data Assimilation Experiment (GODAE), which will improve understanding of meridional ocean overturning and its potential sensitivity to global climate change.

The planning for these programs has been based on the extensive array of ocean-observing satellites and previous global ocean climate programs, notably the World Ocean Circulation Experiment (WOCE) and Tropical Ocean-Global Atmosphere (TOGA). CLIVAR implementation (<http://www.clivar.org>) will, if fully funded, include numerous process components studying the many aspects of North Atlantic and Southern Ocean overturn. These process studies are embedded in the GOOS program, which is also just beginning implementation (<http://ioc.unesco.org/goos>). This global network of spaceborne and in situ ocean observations is critical to our long-term ability to measure, model, and project ocean change and its impact on climate.

5

TERRESTRIAL HYDROLOGY AND VEGETATION FEEDBACKS

SUMMARY

Feedback processes over land are critically important to understanding the climate response over land and its effect on humans. The responses of the hydrologic and energy cycles over land play a critical role in determining the impacts of climate change on water resources, carbon stocks, and agriculture, yet these responses vary widely among different climate models. Unfortunately, basic climate processes such as the response of the land-atmosphere system to diurnal variations of insolation are poorly simulated in current climate models. Snow and ice melting and their associated hydrologic and radiative consequences tend to be poorly simulated, and dynamic vegetation modeling is in its very early stages.

We recommend an integrated analysis of the diurnal and annual cycles of the energy, water (in all its phases), and carbon budgets at the land-surface and through the atmospheric boundary layer for different ecosystems and climatic regimes, including managed ecosystems like irrigated cropland. This analysis—aimed at improving theoretical understanding and model parameterizations—needs to fully integrate land and atmosphere processes and use carefully designed observational metrics to test modeled processes, which must be robust in the face of time-varying land surface properties. Sustained multiyear observations of terrestrial ecosystems, their functioning, and their role in the climate system should be encouraged, to contribute to the development and improvement of process-oriented vegetation models for use with climate models.

TERRESTRIAL HYDROLOGY

The global, annual-mean surface temperature is the most widely used first-order measure of climate change. However, in assessing the impact of climate change the water balance over land is at least as important. Terrestrial surface hydrologic changes are important for human requirements such as drinking water, sanitation, agriculture, transportation, and energy supply. These changes are also important for the response of natural ecosystems on land to human-induced climate change. The variables used to measure changes in the surface water balance are precipitation, evaporation, and runoff rates, as well as soil and surface water storage. These quantities are related to temperature, wind, cloudiness, vegetation characteristics, and other climate system variables.

For this report the primary interest in terrestrial hydrology is its role in climate change feedbacks. In the tropics, interactions among land hydrology, vegetation, and surface energy balance can foster feedback mechanisms that may cause expansion or contraction of deserts, for example. In middle latitudes interactions between winter snowfall, spring snowmelt, and summertime convection can lead to potential changes in water availability during the growing season that may pose a substantial threat to agriculture. Earlier snowmelt can lead to more rapid drying, reduced summertime precipitation, and increased surface temperature over land. These feedbacks and the response of mid-latitude land hydrology to climate change and global warming are highly uncertain. Better characterized or reduced uncertainty in projections of the response of land hydrology to global warming would have important implications for the development of mitigation and adaptation strategies.

The feedbacks between soil water, evaporation, precipitation, and runoff are an integral part of the hydrological cycle over land, as are the interaction of vegetation and the frozen hydrology (ground and snow) at high latitudes, with their impacts on albedo and the availability of water for evaporation. Climate change, driven globally by the global rise of greenhouse gases, will have regional impacts on this hydrological cycle, differing across latitude and across continents. Currently our confidence in regional projections is limited by our lack of understanding of the processes and feedbacks controlling the precipitation-evaporation difference, both over land (where it is fundamental to the long-term drift of the hydrological cycle) and over the ocean (where it is one key component impacting the surface energy budget and changes in the thermohaline circulation). Improving confidence in regional temperature and freshwater resource projections is also intimately linked to a better understanding of the coupling between surface processes and the atmospheric boundary layer.

In addition to the above concerns, recent estimates are that over 30 percent of the discharge of the world's rivers is actively managed. This has occurred through the construction of some 40,000 major dams and diversion structures, which have been capable of changing the hydrologic regimes of the world's major rivers and potentially the global water cycle. The feedbacks between the managed portion of the terrestrial water cycle and other components have received virtually no attention, but are potentially important because the effects of water management on natural hydrographs are far larger than those projected to be caused by climate change. These changes in the discharge regimes of large rivers are known to have changed ocean circulation in the vicinity of river mouth estuaries, and perhaps at larger scales. Furthermore, changes in vegetation, many of which are related to water management, are known to have caused changes in the local cycling of moisture in the land-atmosphere system (e.g., Stohlgren et al., 1998), and anthropogenic changes in land cover due to management have been shown to have affects at global scales (Chase et al., 1996, 2000).

Reducing model uncertainty can be achieved in part through improved understanding and projections of the regional long-term drift of the hydrologic cycle over land. These improvements are fundamental to projecting ecosystem dynamics on decadal timescales. At present, coupled global models differ widely in their regional forecasts for future trends in the hydrologic cycle. The U.S. Water Cycle Initiative (USGCRP, 2001) has outlined several important science goals that need to be addressed to improve our ability to model the global and regional water cycle. A focused research effort is required to improve these models.

From a scientific perspective this area of research is ripe for progress. Indeed, in the past five years considerable progress has been made in understanding soil water feedback, in making soil water measurements, and in the development of land surface data assimilation systems that indirectly provide soil water fields on continental to global scales. The challenge ahead is synthesis, because the water cycle plays such a central role and it interacts directly with much of the climate system, and in particular over land with the energy and carbon cycles.

Overview of Terrestrial Hydrology Feedbacks

Soil Water Feedbacks

The land-surface reservoirs of available soil water are small compared to the ocean reservoir, typically of order 0.1-0.6 m of water. However, their role is crucial to the surface climate over land because evaporation from the near surface soil layer and transpiration of water extracted by vegetation from their root zone is a major component of the surface energy balance. Over wet soils the daily mean Bowen ratio (the ratio of the sensible to latent heat flux) may be of order 0.5, while over dry soils when the vegetation experiences water stress, the Bowen ratio may exceed 1. In turn the increased evaporation over wet soils can lower maximum surface temperature by several degrees.

A feedback arises because increased surface evaporation over large land areas gives rise to increased precipitation (e.g., Beljaars et al., 1996), which maintains soil water levels. This is primarily a feature of the warm season, and wet regions of the tropics. Over the continents as a whole, precipitation minus evaporation (P-E) is positive, which contributes the runoff of fresh water to the oceans. Correspondingly E-P is positive over the oceans. However, the balance between P and E varies widely, both spatially and temporally. The monsoon circulations concentrate the flux of moisture from ocean to continents. Over large regions of land in summer (remote from the summer monsoon) P is more closely in balance with E. There is also a large seasonal cycle in which winter precipitation adds to soil water reservoirs in mid-latitudes and to snow accumulation at high latitudes, and this is drawn down in spring and summer by both runoff and evaporation. The diurnal cycle of precipitation and cloud is also involved, because transpiration depends on daytime solar radiation (and thus involves critically the shortwave cloud feedback), while the equilibrium temperature of the land-surface (which determines outgoing longwave radiation) is sensitive as well to the impact of clouds on the long wave balance, especially at night.

Although it seems clear that warming will accelerate the hydrological cycle, the net change of P-E and runoff over land, particularly in the warm season for specific regions, remains uncertain. At high latitudes it is possible that the likely increase in winter precipitation will lead to increased snowpack and spring runoff, but the impact on summer soil water, evaporation, and precipitation remains uncertain.

The complex couplings among precipitation, evaporation, soil water, runoff, the cloud fields, net radiation balance, and the vegetation on the diurnal timescale have not yet been modeled satisfactorily for the present climate. Typically this leads to fundamental errors in the diurnal cycle of precipitation (Betts and Jakob, 2002). The diurnal time scale, together with the continental scale circulation dynamics and the seasonal cycle, must be accurately modeled so that confidence can be assigned to projections of land hydrology changes associated with global warming.

Snow-Albedo Feedback

One of the most important climatic characteristics of snow is its albedo. Fresh snow on a fully covered surface has an albedo of approximately 0.8. Aging of the snow will reduce this to about 0.4. Snow in tree-covered landscapes has an albedo of about 0.2 to 0.4 depending on the vegetation cover type.

In the fundamental snow-albedo feedback a decrease in snow extent decreases the surface albedo, which tends to increase surface temperature. These changes can affect large-scale circulation and planetary albedo which in turn, can affect subsequent snow precipitation and melt rates. There are many confounding factors to this picture, including the effects of vegetation and snow age.

Trees and other vegetation can protrude over snow and mask its high albedo. As a result treeless areas have a higher albedo when snow is on the ground than do forests. Numerous climate model studies have found that the presence of the boreal forest warms climate compared to tundra (Bonan et al., 1992; Douville and Royer, 1996). Forest and tundra ecosystems also differ in how they partition net radiation into sensible and latent heat fluxes. For example, albedo differences in snow-covered and adjacent snow-free forests can result in local energy circulations with advection of energy to the forests (e.g., Taylor et al., 1998)

At the regional scale the removal of snow cover may affect the thermal and dynamical structure of the atmosphere, but the temporal persistence of these effects is uncertain (Yeh et al., 1983). To date, one of the strongest pieces of evidence of a snow cover and weather feedback is the connection between springtime air temperature biases (5-10°C low in ECMWF weather predictions due to specified high-latitude snow albedo, which was biased high (by approximately 0.4) in the model (Viterbo and Betts, 1999). This result demonstrates the effect of large-scale snow cover on near surface air temperature, with the correction of the albedo bias correcting the air temperature bias.

In general the existence of a feedback mechanism between snow cover extent and continental- to global-scale weather and climate requires that snow processes affect atmospheric circulations at these scales. There are model results that suggest such an effect. For example, the interannual variations of the Asian summer monsoon rainfall have been significantly correlated with the tropical sea surface temperature and the Eurasian snow cover anomalies (Bamzai and Shukla, 1999; Corti et al., 2000).

In general, current models represent mean global snow cover fairly well but are less accurate in representing interannual snow cover variability. In general even off line terrestrial hydrologic models, forced with observed meteorology and radiation, tend to underestimate the observed variability in the record. The biggest difference in the predictions among models occurs in snow transition regions. Models do fairly well in the snow accumulation season but differ greatly from observations in the melt season, resulting in different predicted time of end-of-melt that varies by two to three weeks. This can affect the subsequent prediction of the onset of vegetation activity.

The largest modeling challenge related to snow melt is representing sub-grid snow cover at GCM grid scales. Accurately estimating the albedo of retreating snow cover involves accounting for factors such as snow patchiness and snow age. The modeling of these effects is well understood, but has mostly been carried out over idealized domains where the contrasts may not represent the variability observed in natural landscapes. The modeling of natural domains requires high-resolution modeling and the accompanying forcings.

In validating model predictions against observations a significant problem is the observational bias that results from the placement of instrumentation in clearings and the rather different snow dynamics of forested and cleared areas.

At the other end of the scale spectrum global modeling assessments of the snow-climate feedback have been rather limited and the results show discontinuous areas having correlations between snow extent and the Indian monsoon rainfall. The scope of these studies should be expanded to rigorously diagnose large-scale effects of snow cover on circulation and the planetary albedo. An important part of this work is the boundary layer coupling between the snow-covered surface and overlying atmosphere.

Modeling the melting of snow in springtime is important to correctly simulating the role of snow in climate feedbacks over land. Key issues in snow melt modeling include

- **improving space-time distribution of snow.** During the snow accumulation period most model prediction problems are largely attributable to precipitation and temperature surface forcing, while during snow ablation periods poor snow model predictions are more closely related to the model parameterizations related to surface energy transfer.

- **evaluating errors in space-time extent.** There is a need to evaluate and improve the quality of data; use this data for error diagnostic studies with a focus on transient zones at regional and continental scales; and better utilize offline evaluation methods.
- **developing better global databases for model parameters** (e.g., surface roughness, vegetation solar radiation extinction, canopy closure, snow patchiness functions).
- **developing point or small area datasets** for offline model evaluation across a range of snow climatologies and vegetation types, and for the evaluation of new model parameterizations.

VEGETATION FEEDBACKS

The traditional view of terrestrial vegetation is that community composition and ecosystem structure are determined by climate. However, this is only part of the interaction of ecosystems with climate. Terrestrial ecosystems affect climate through exchanges of energy, water, momentum, CO_2, and other radiatively important atmospheric gases. Changes in community composition and ecosystem structure alter albedo, surface roughness, stomatal physiology, leaf area, rooting depth, and nutrient availability and in doing so alter surface energy fluxes, the hydrologic cycle, and biogeochemical cycles. As a result, changes in ecosystem structure and function and the replacement of one ecosystem with another in response to climate change feed back to influence climate. The IPCC TAR has identified changes in land cover as a potentially important climate feedback.

Most studies of vegetation feedbacks have focused on biogeophysical processes related to energy, moisture, and momentum exchange with the atmosphere. Biogeochemical feedbacks are only now being included in climate models (Cox et al., 2000; Friedlingstein et al., 2001). This review focuses on biogeophysical feedbacks, considering a continuum of processes and time scales from physiological (minutes) to phenological (seasons) to vegetation dynamics (decades to hundreds of years).

Overview of Vegetation Feedbacks

Stomata Feedback

The partitioning of net radiation into sensible and latent heat fluxes by vegetation is regulated in part by canopy conductance. Studies of the physiological response of plants to short-term exposure to enhanced CO_2 concentrations routinely find reduced stomatal conductance and greater photosynthesis. Climate model simulations in which stomatal conductance decreases with a doubling of atmospheric CO_2 routinely show decreased latent heat flux, increased sensible heat, and surface warming over large vegetated regions in summer (e.g., Sellers et al., 1996). In general, the physiological effects of doubled CO_2 amplify the warming associated with the radiative effects of doubled CO_2.

Previous climate model studies highlight the potential for physiological feedbacks from vegetation (e.g., Sellers et al., 1996). It is quite likely that changing atmospheric CO_2 concentration will alter the physiology of plants and through this affect climate. However, we cannot yet quantify this feedback with certainty and rank it relative to other climate feedbacks. Uncertainty in its magnitude and importance arise for several reasons. First, physiological processes operating at the scale of an individual leaf need to be scaled to a canopy of leaves and then to a landscape of thousands of plants. There are few observations to guide this scaling, as most studies of stomatal conductance and its response to CO_2 are obtained from leaf measurements. Second, most studies examine the short-term response of plants to CO_2. Long-term acclimation to high CO_2 may alter the short-term reduction in stomatal conductance. Third, the reduction in stomatal conductance observed in the laboratory may not be realized in the field, where many other environmental factors (e.g., dry soil, low nutrient availability) also limit photosynthesis. Finally, atmospheric CO_2 is also known to alter the allocation of carbon to the growth of foliage, stem, and root biomass and the chemical quality of plant material. This is likely to affect climate by changing, for example, the amount of leaf area from which heat and moisture can be exchanged with the atmosphere or by changing the amount of carbon stored in the soil.

Leaf Area Feedback

The seasonal emergence and senescence of leaves on deciduous trees alters albedo and sensible and latent heat fluxes and in doing so alters surface climate, including temperature and transpiration (Fitzjarrald et al., 2001; Schwartz, 1999). In the eastern United States, springtime air temperatures are distinctly different after leaves emerge (Schwartz, 1992, 1996; Schwartz and Karl, 1990). This temperature discontinuity over a period of less than a few weeks is related to increased transpiration upon leaf emergence that cools and moistens air. A similar distinct seasonal pattern to air temperature coinciding with the absence or presence of leaves on deciduous trees is seen in west central Canada (Hogg et al., 2000).

Because of the importance of foliage in regulating surface climate, improved representation of leaf area and its phenology are being implemented in climate models. In general, higher leaf area increases evaporation over vegetated regions in summer provided there is sufficient soil water (e.g., Buermann et al., 2001). As a result surface temperature cools and precipitation increases. Prognostic models of leaf area in which the amount of foliage depends on temperature, precipitation, and plant productivity are being included in the land models used with climate models. One study with interactive leaves found increased air temperature and reduced evaporation and precipitation over extratropical regions of the Northern Hemisphere in summer as result of lower leaf area (Dickinson et al., 1998).

As with stomata, leaf area must be considered a “known unknown” in its magnitude and importance as a climate feedback. Observations of temperature and leaf phenology demonstrate a change in temperature with leaf emergence, but prognostic leaf phenology is a new process for land-surface models. There is not a long history of climate model experiments to demonstrate the robustness of this feedback among climate models or to determine the key ecological processes regulating leaf area in a coupled climate-vegetation model.

Biogeography Feedback

Vegetation changes naturally over time in response to recurring disturbances and also in response to climate change. Fires, insect outbreaks, and windstorms that kill large tracts of trees initiate a process of revegetation and ecosystem recovery known as plant succession. A forest, for example, may undergo successive transformation from bare ground to herbaceous species to shrubs to young forest to mature forest following fire. Climate change that may, for example, convert a forest to grassland is superimposed on this successional development. This vegetation dynamics and change from one vegetation type to another alters numerous surface properties such as albedo, roughness, stomatal physiology, leaf area, and rooting depth and in doing so can alter climate.

The impact of vegetation dynamics on climate is seen regionally in the Sahel of North Africa and along the boreal forest-tundra ecotone. Precipitation limits the northward advancement of grasses and shrubs into the Sahara Desert. Temperature limits the northern extent of trees into tundra. In both these regions climate model simulations show amplification by vegetation of the climate response to changes in precipitation or temperature. Expansion of grasses and shrubs into desert in response to enhanced summer precipitation results in more precipitation (Claussen et al., 1999; de Noblet-Ducoudré et al., 2000; Kutzbach et al., 1996). The boreal forest warms climate compared to tundra as a result of the lower winter albedo of forest (Bonan et al., 1992; Foley et al., 1994).

Global vegetation models have been developed to allow interactive coupling of climate and vegetation. One approach, known as asynchronous equilibrium coupling, takes advantage of the relationships between climate and biogeography to interactively change vegetation cover (Claussen, 1994). Climate is simulated with an initial vegetation cover. This climate is used in a biogeography model to simulate the geographic distribution of vegetation. This map is then input to the climate model to obtain a new climate. Climate is iterated in this manner several times until a stable solution is obtained. Another type of model, known as a dynamic global vegetation model, explicitly simulates transient vegetation dynamics (Foley et al., 1998, 2000).

Coupled climate-vegetation models show that vegetation feedback amplifies the climate response to solar radiation or atmospheric CO_2. For example, the colder climate as a result of reduced solar radiation and lower atmospheric CO_2 some 115,000 years ago is not in itself enough to initiate an ice age. However, the associated reduction in the geographic extent of the boreal forest and the expansion of tundra due to the cold climate produces additional cooling that is sufficient to initiate an ice age (de Noblet et al., 1996). Coupled climate-vegetation models highlight the importance of the treeline in reinforcing the cold high-latitude climate of the last glacial maximum 21,000 years ago and the high-latitude warming 6,000 years ago (Kubatzki and Claussen, 1998; Levis et al., 1999; Texier et al., 1997). Other studies show that changes in the geographic extent of vegetation enhance the orbitally induced summer monsoon 6000 years ago in North Africa (de Noblet-Ducoudré et al., 2000; Doherty et al., 2000; Texier et al., 1997). The doubling of atmospheric CO_2 from pre-industrial levels is likely to result in changes in ecosystem structure and function in response to altered temperature, precipitation, and CO_2 fertilization. Climate simulations with coupled climate-vegetation models show large changes in climate as a result of vegetation changes (Betts et al., 1997, 2000; Levis et al., 2000).

As with stomata and leaf area, the inclusion of interactive vegetation in climate models is relatively new. Initial work with these models has demonstrated the potential for large feedbacks with climate. Future work must demonstrate the robustness of these feedbacks and reduce the uncertainty in these simulations.

Key aspects of the required research strategy are discussed below.

DEVELOPING A SCIENTIFIC STRATEGY

As described in the previous sections, several potential feedbacks exist between vegetation and climate, including radiative (albedo), physiological (stomata), micrometeorological (sensible and latent heat), hydrological (snow, soil water), biogeochemical (carbon and other greenhouse gases), and ecological (leaf area, biogeography). These are often viewed as separate areas of research. In particular, our understanding of fundamental vegetation processes and their inclusion in climate models suffers from the broad multidisciplinary scope of the potential interactions. There is not a coordinated research agenda to understand and model their potential feedbacks.

We still lack the simplified theoretical models needed to generalize our understanding of the feedbacks between the coupled energy and water cycles across different climatic regimes. Theoretical work on the diurnal cycle of the coupled land-surface-convective boundary layer system for different ecosystems and seasons would lead to improved understanding of this basic climatic control on cloud, radiation, and water cycle feedbacks over land. In addition, more work on the coupling of soil water, resistance to evaporation, lifting condensation level, and cloud base (observable from the ground by lidar ceilometers) would deepen our understanding of the land-surface and soil water controls on atmospheric subsaturation, cloudiness, and precipitation. Theoretical work on feedbacks and other interactions between ecosystems, biogeochemistry, and hydroclimatic processes at a very wide range of time and space scales also requires further development.

Progress in understanding terrestrial feedbacks depends critically on both systematic analysis of data generated by advanced, integrated observational datasets, and on careful testing and improvement of coupled modeling systems. Advancements in understanding of the processes responsible for terrestrial hydrology and vegetation feedbacks could be greatly facilitated by a program of integrated observations and analysis of the diurnal and seasonal cycles of the energy, water, and carbon budgets at the land-surface and through the atmospheric boundary layer. In addition, longer-term measurements and analyses of interannual ecosystem and hydrologic variability are important.

An important focus of research on terrestrial feedbacks should be on improving the parameterization of dynamic vegetation in climate models. This work must treat energy, water, carbon, and nutrients as a single system rather than as disciplinary components. Observations must be made to better understand the natural processes, improve the parameterizations, and test those parameterizations in coupled models. By focusing systematically on this joint observational and modeling problem, the various scientific communities that monitor, study, and model terrestrial vegetation may be spurred toward better integration in much the same way that coupled atmosphere-ocean models led to integration of atmospheric and oceanic sciences.

As discussed below, a global network of surface flux tower sites exists (Baldocchi et al., 2001), but many analyses have a narrow focus on, for example, the carbon balance at the site rather than the full energy, water, and carbon balance and their coupling to the boundary layer, and its cloud field. It is rare for example that sites measure boundary layer height, structure, cloud base and cloud cover (even though this can be done remotely) or the soil water profile. Yet the photosynthetic processes are tightly linked both to the soil hydrology, the surface energy balance (which depends on the clouds and the radiation field, whether direct or diffuse), as well as the coupling to the boundary layer over the diurnal cycle. Our ability both to measure (the fluxes) and to model the nighttime stable boundary layer is still unsatisfactory, and progress probably requires a careful study of the coupled water, energy, and CO_2 budgets.

Therefore, an integrated analysis should evaluate and improve model representation of physical processes known to affect the diurnal, seasonal, and interannual cycles, using detailed field site data, as well as routine observations and simplified models.

Observations

Perhaps the most fundamental problem regarding the understanding of vegetation feedbacks is a lack of global datasets with which to evaluate existing land-surface processes in climate models. In addition to being critical for understanding terrestrial climate feedbacks, observations of essential ecosystem variables, such as biome type, net primary production, and carbon stores, are integrators of climate and therefore valuable diagnostic measures of models' overall ability to simulate surface climate. Unfortunately the existing observational efforts fall short of what is needed.

Field programs such as FIFE (First International Satellite Land Surface Climatology Project Field Experiment), BOREAS (Boreal Ecosystem-Atmosphere Study), and LBA (Large-Scale Biosphere-Atmosphere Experiment in Amazonia) provide tower flux data (e.g., sensible heat, latent heat, CO_2) but only for particular locales. The inclusion of interactive vegetation provides additional ecological data, such as net primary production, carbon storage, leaf area, and biogeography, with which to test climate models.

The AmeriFlux network of permanent towers allows for sustained multiyear observation of particular ecosystems (Wofsy and Hollinger, 1998). It is part of a global network known as FLUXNET (Baldocchi et al., 2001). However, without the broad multidisciplinary focus of FIFE, BOREAS, or LBA many of these tower sites lack the suite of ancillary hydrological and ecological data needed to understand and model the observed fluxes. Most tower sites do not include measurements and analysis of the full energy, water, and carbon balance and their coupling to the boundary layer, and its cloud field. We recommend that these sites expand their focus to include such interactions, which are important for climate models on the boundary layer scale.

The National Science Foundation's Long Term Ecological Research (LTER) program allows the longest (in some cases multi decadal) sustained observation of particular ecosystems. These sites have been chosen to span the range of global biomes (e.g., tundra, boreal forest, grassland, desert). The focus of research is decidedly ecological, emphasizing community composition, ecosystem structure, and their response to environmental change. Some sites (e.g., Harvard Forest) have towers.

Observations of terrestrial ecosystems, their functioning, and their role in the climate system must be sustained over multiyear periods if they are to be of greatest use in the development and improvement of process-oriented vegetation models for use with climate models. A network of such observation sites spanning the range of global biomes is desirable. This suggests that coordination between the AmeriFlux and LTER programs is important to help ensure that a diverse set of biomes is observed.

Measurements using aircraft, such as the recent CRYSTAL and COBRA studies, should also be used to help diagnose the ability of global models to simulate the budgets of water, energy, and carbon for river basins and major ecosystems up to the continental scale. This work should involve a tight integration of land and atmospheric measurements and data assimilation with climate modeling.

To develop the observational basis to improve and test models, both the modeling and remote-sensing communities must work together to better define the vegetation parameters that are observable by satellite and that are critical to modeling vegetation feedback in the climate system. Some of the parameters that are emerging from a dialogue between these communities are leaf area and its phenology. Multiyear leaf area index datasets have been and are being developed for use with climate models (e.g., Buermann et al., 2001). These data products can be used as prescribed leaf area or as a validation of prognostic leaf area (Dickinson et al., 1998, Buermann et al., 2001). Another key emerging data product is fractional tree cover, which can also be used as an input to and validation of models (Bonan et al., 2002). Sustained monitoring of these parameters and extension of these records in the past should be encouraged to allow the modeling community to quantify the vegetation forcing of climate. At the global scale key satellite-derived data products, such as leaf area index, must have at least monthly temporal resolution to be of greatest use in improving and testing climate simulations. In addition, the data products should continue to expand the record to help better account for interannual variability in leaf area.

Much of the global evaluation of the surface climate is still based on 2-m air temperature, humidity, pressure, wind, and precipitation interpolated from station observations. However, many important components of the surface water and energy budget are not routinely measured, and some that are measured at selected experimental sites may not be freely available in the public domain. The shortwave and longwave radiation balances are only recorded at relatively few baseline radiation measurement sites, although satellite-based estimates of the surface short-wave balance have achieved a fair degree of accuracy. The surface fluxes of sensible and latent heat (together with some components of the radiation balance) are measured on flux towers at some 50 or more sites globally, although not all these data are freely accessible. Up-scaling these measurements over carefully selected stands of vegetation to give regional averages (of, say, evaporation) is not straightforward. Estimates of regional evaporation can be made using river basin hydrologic models from observations of precipitation and river runoff. However, regional estimates of precipitation can only be derived from point rain gages and calibrated radars, where available, or from satellite retrievals. Consequently precipitation estimates also have considerable uncertainty and may be biased low when precipitation is frozen.

Important subsurface variables, such as soil temperature and soil water, are also not routinely measured, although they are now being measured in a few important networks, such as the Oklahoma Mesonet and some AmeriFlux sites. The measurement of the freeze-thaw of the surface soil layer is now possible from satellite microwave sensors, but this product is not yet routinely available. Satellites can measure snow cover, but the important measurement of snow water equivalent still presents problems. All satellite measurements of the soil and surface layers have difficulties under forest canopies

A promising approach for developing global soil water fields is the extension of the land data assimilation system (LDAS) pioneered at the National Centers for Environmental Prediction (NCEP) for the regional Eta model. At present, two groups (one in the United States and one in Europe) are developing a global LDAS, using a mix of satellite and surface data to provide the surface radiation budget and precipitation needed to force offline a land-surface-vegetation-hydrology model, which will give subsurface fields of temperature and moisture. Global cooperation is here essential since not all the necessary data has been freely shared in real time in the past. The future availability from satellite of global maps of near-surface soil wetness will provide further useful input.

Modeling

Because many of the key variables, especially below the surface, are not measured globally, the surface temperature, soil water, and surface energy balance in data assimilation systems is largely a product of a fully coupled land-surface-vegetation-atmosphere model, often constrained by the observed atmospheric diurnal cycle of temperature and humidity near the surface. In forecast and climate models the computed land-surface boundary condition depends on a large number of parameterized submodels, all of which are highly coupled and tend to exhibit considerable differences between each other and with observations. The relationships among the variables in these models is complex, and thus lack of knowledge in one area can have cascading effects. For example, the surface radiation budget depends on the model parameterizations for the cloud fields (which are not explicitly resolved in a global model), while the cloud fields depend on the dynamics, and the moisture field which in turn depends on moisture transports and the surface evapotranspiration. Soil water depends not only on model precipitation and evaporation (coupled to photosynthesis) but also on the subsurface hydrology, which is strongly dependent on the lateral heterogeneity.

The fundamental links between land-surface hydrologic processes, clouds, and precipitation depend in global models on the parametric representation of sub-grid scale boundary layer and cumulus convection. No completely satisfactory parameterization exists for convective clouds, which typically have organization on unresolved scales of 50 km and below. Boundary layer parameterizations are typically quite separate (with different formal closures) and poorly coupled to convective parameterizations in large-scale numerical models, when in nature there is a smooth continuum over the diurnal cycle. Over land in the tropics, for example, as the boundary layer grows after sunrise shallow clouds quickly form, deepen into cumulus congestus, and then organize into precipitating cloud bands, producing a wide range of mid- and high-level clouds, all of which impact the diurnal cycle of the surface radiation budget at the same time as they impact the surface hydrologic budget. From a climate perspective this diurnal cycle of convection plays an important role in the shortwave and longwave cloud feedbacks discussed in Chapter 3. Cloud resolving models are proposed in Chapter 3 as one tool with which to address some of these fundamental unresolved issues of the interaction between different time and space scales, although it is not yet possible to resolve simultaneously both boundary layer clouds and deep convection. To comprehensively characterize and possibly reduce uncertainty in the hydrological cycle of our climate models requires a major ongoing effort both in synthesis and in rigorous diagnostics that cuts across all modeling, theoretical, and observational communities.

Many areas of dynamic vegetation modeling, which are vitally important for simulating long-term feedbacks between the biota and climate, are still in stages of rapid development. It will be important to test the newly emerging prognostic ecosystem and leaf phenology algorithms in coupled climate-vegetation-land-surface models using both existing data and the new data sources outlined in the previous sections.

Many of the feedbacks associated with vegetation occur at longer time scales (centuries) than can be observed with existing observing systems. Paleoclimate research is an important activity to understand vegetation feedbacks on climate. The last glacial maximum and 6,000 years before present have emerged as key periods of focused research demonstrating that inclusion of interactive vegetation improves the simulated climate. Paleoclimate research must be integrated with and indeed is critical to the implementation, testing, and improvement of dynamic vegetation in climate models. The community should work to define standard paleoclimate experiments (e.g., last glacial maximum, 6000 B.P.) that are used to evaluate the coupled climate-vegetation model and highlight the importance of particular vegetation feedbacks (e.g., forest-tundra ecotone, green Sahara).

Evaluating Progress

A clear metric for progress in the coming decade would be the accuracy with which our earth system models can reproduce, for example, the observed diurnal and seasonal variations of the hydrological cycle over land. The short-term modes of variability, like the diurnal, are well represented in even a few annual cycles, while interannual variability requires a longer statistical period. Reanalysis of the past 40 to 50 years of atmospheric data is now available (with new reanalyses in progress). The hydrological records of the past few decades are also being synthesized for global use. Flux site data records are approaching a decade in length. An accuracy of perhaps 5 percent in the key terms in the surface hydrology budget (precipitation and evaporation) would be a realistic target for the coming decade.

The ability of climate models to successful reproduce the terrestrial carbon cycle provides a clear metric to evaluate progress in vegetation models. The carbon cycle integrates across temperature, precipitation, energy fluxes, and the hydrologic cycle and the influence of these on various ecological processes. Tower flux data, ancillary ecological data, satellite-derived data products, and measurements of atmospheric carbon dioxide provide a wealth of critical data with which to constrain and evaluate the simulated carbon cycle.

6

ATMOSPHERIC CHEMICAL FEEDBACKS

SUMMARY

Understanding atmospheric chemistry feedbacks are crucial not only for future climate projections but also to connect measured concentrations of greenhouse gases with their emissions and for formulating control strategies and policies. Both gas phase and aerosol chemistry are influenced by temperature, humidity, cloudiness, and precipitation and have the potential to feed back on climate change. Both tropospheric and stratospheric chemical processes interact with temperature, humidity, circulation, and air composition changes. The oxidizing capacity of the atmosphere and the processes that convert effluents into pollutants may be altered by climate change. Current knowledge of aerosol composition, surface characteristics, and their spatial and temporal variations are inadequate.

More research on atmospheric processes is required, with the goal of representing them more comprehensively in global climate models to elucidate the feedbacks. The physical and chemical processing of aerosols and trace gases in the atmosphere, the dependence of these processes on climate, and the influence of climate-chemical interactions on the optical properties of aerosols are the key areas that require better understanding and quantification. The recent improvements in the instrumentation for in situ aerosol characterization (e.g., chemical composition of aerosol particles on individual particle basis), optical extinction, and scattering measurements will allow rapid progress in this area. The ability to monitor aerosols from satellites and LIDAR (aircraft and ground-based) will allow large-scale characterization of aerosol climatologies and properties. Deployment of these instruments in clear and cloudy conditions in well-planned field studies augmented by laboratory and modeling studies is needed. Development of aerosol climatologies along with other variables such as emission inventories is essential and feasible.

Greenhouse gases (e.g., water vapor, carbon dioxide, methane, nitrous oxide, ozone, chlorofluorocarbons) and aerosols in the atmosphere interact with solar and terrestrial radiation and thus alter the radiative balance of Earth's climate system. Human activities have clearly altered the atmospheric abundance of many greenhouse agents since the pre-industrial era (circa 1750). Humans alter some by direct emissions of the agents themselves (e.g., the gases CO_2, CH_4, N_2O, and CFCs, and the aerosol soot), some through the emissions of precursors that through atmospheric chemistry impact the greenhouse agents (e.g., emissions of SO_2 are oxidized to form sulfate aerosol, or emissions of NO make O_3 and destroy CH_4), and some through changes in temperature and other related factors (e.g., water vapor abundance). The largest individual greenhouse gas contributions to the overall human-driven rise in radiative forcing since 1750 is 1.46 W m^{-2} from CO_2, 0.48 W m^{-2} from CH_4, 0.35 W m^{-2} from O_3, 0.17 W m^{-2} from CFC-12, and 0.15 W m^{-2} from N_2O (IPCC, 2001a).

Atmospheric chemical feedbacks arise when alterations in the surface temperature, precipitation, and other changes in climate interact with air chemistry to alter the abundance or properties of greenhouse gases or aerosols, which then produce an additional climate change. It is also important to note that interactions between climate and air chemistry can produce regional changes in air quality that may be a very important aspect of climate change.

Water vapor, an important greenhouse gas, is predominantly determined in the troposphere by physical and dynamical processes in the natural climate system. Only in the stratosphere are chemical processes central in the determination of the water vapor concentration. To a first approximation, atmospheric chemical processes do not affect the abundance of water vapor and carbon dioxide in the troposphere. In the stratosphere, however, approximately 50 percent of water vapor (Kley et al., 2000) is generated by methane oxidation and is therefore influenced by chemical changes in the troposphere. Changes in the abundance of water vapor greatly affect chemical changes in the atmosphere. These processes affect such species as methane, ozone, and aerosols. For example, an increase in atmospheric water vapor due to increases in sea surface temperature will increase the production of the OH radical, the agent that cleanses the troposphere and controls the abundances of such greenhouse gases as methane and tropospheric ozone; changes in cloud abundance and cloud water content alters the rates of heterogeneous and multiphase chemical reactions. Changes in cloud coverage could also alter the actinic radiation that drives the photochemistry in the troposphere. Understanding how chemical processes are altered by changes in temperature and water abundance in the atmosphere, and how chemical processes alter the concentrations of greenhouse gases and aerosols, constitute an important area of climate research. Climate-air chemistry feedback is obviously essential for projecting the consequences of the current emissions and for making policy decisions regarding regulating, decreasing, and trading emissions.

While the long-lived greenhouse gases (e.g., CO_2) are well mixed in the troposphere, other short-lived gases and aerosols are not well mixed and hence extremely variable in space and time. One of the keys to understanding the geographic distribution of future radiative forcing is the ability to project the abundance of greenhouse gases and aerosols and their spatial and temporal variations. Ozone in particular is an important species because it is produced in the atmosphere by photochemical processes. Aerosols are also often generated in the atmosphere. The distributions of both are controlled by their rates of production and destruction, as well as their atmospheric transport.

There are a few other factors related to chemical processes that are of central importance to climate and its variation. Rapid, nonlinear changes in greenhouse gases, such as the release of methane from clathrates, can lead to catastrophic changes.

AN EXAMPLE OF THE MULTIPLE DIMENSIONS OF CLIMATE-AIR CHEMISTRY FEEDBACK

Methane is the greenhouse gas whose increase since the pre-industrial era provides a climate forcing that is second only to carbon dioxide. Methane is also a chemically active species that affects the abundance of the OH radical, the most important tropospheric oxidizer. Therefore, if methane is emitted into the atmosphere, it can decrease the abundance of OH radicals, which in turn will make methane degrade more slowly. This is a purely chemical feedback. Climate enters the feedback process if the rate of methane formation or destruction is affected by a climate variable such as temperature or water vapor abundance.

This example also shows the possibility that the climate response to methane emission can also change the lifetime of methane in the atmosphere. To a crude approximation, the atmospheric lifetime of methane, τ_{CH_4}, is given by:

$$\tau_{CH_4} = \frac{1}{\left[k_1(\mathrm{T}) \times [\mathrm{OH}]\right]}$$

where $k_1(T)$ is the rate coefficient for the reaction of OH with methane in the atmosphere at the temperatures in the atmosphere (DeMore et al., 1997; Vaghjiani and Ravishankara, 1991). The product of k_1 and [OH] is averaged over the entire region where methane is degraded. Because the abundance of OH can be decreased by an increased emission of methane, clearly the lifetime of methane will increase. The change in temperature will alter the rate coefficient k_1 and hence alter the atmospheric lifetime and abundance of methane.

Changes in water vapor will also greatly affect OH since the primary process that produces OH in the atmosphere involves a competition between water vapor and nitrogen (oxygen) for the removal of $O(^1D)$ produced by the photolysis of ozone.

$$O_3 \xrightarrow{h\nu} O(^1D) + O_2$$

$$O(^1D) + N_2/O_2 \rightarrow O(^3P) + N_2/O_2$$

$$O(^1D) + H_2O \rightarrow 2\ OH$$

This example also shows how changes in other atmospheric constituents feed back on greenhouse gases through alterations in their lifetime. Ozone levels affect the abundance of other radiative gases and alter the abundance of ozone itself. Therefore, it is very important to note the feedbacks that involve ozone, an important anthropogenic greenhouse gas. The way ozone affects the abundance of chemically active radiative gases is through the alteration of the capacity of the troposphere to oxidize such species. For example, an increase in ozone abundance in the troposphere will lead to an increase in the production of OH, which in turn affects the tropospheric lifetimes of species. An increased oxidative capacity, when coupled with emissions of hydrocarbons and nitrogen oxides, leads to further production of ozone itself (i.e., an increase in hydrocarbons and nitrogen oxides leads to more production of ozone [Seinfeld and Panis, 1998]).

Clearly the above example is not simple. An increase in gas phase hydroxyl radical can also enhance the abundance of gas phase hydrogen peroxide (H_2O_2). H_2O_2 oxidizes SO_2 in liquid droplets. Thus, even though an increase in OH will increase the sulfate production rate (either through gas phase or through liquid phase reactions), the consequences to the atmosphere could be different. Gas phase production of H_2SO_4 can lead to a burst of new particles when there are few existing particles, while liquid phase oxidation will only grow existing particles (Seinfeld and Panis, 1998). The consequences of a larger number of particles are different from the same mass of larger particles. For example, the former may lead to brighter clouds than the latter given the same amount of water vapor (Twomey, 1991).

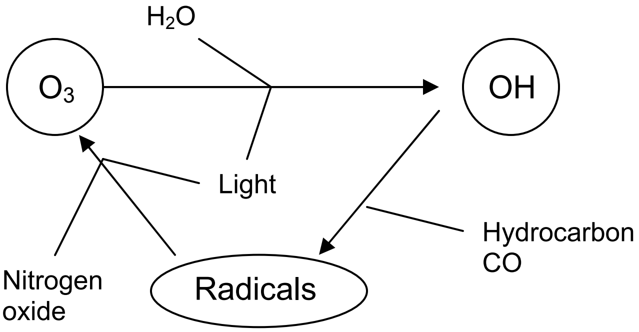


FIGURE 6.1 A simplified illustration of feedbacks between ozone and the hydroxyl radical.

Unlike other greenhouse gases, ozone is photochemically produced from other emissions (Figure 6.1). This unique nature of ozone makes its abundance highly susceptible to changes in other atmospheric abundances and conditions. In addition to its direct role as a greenhouse gas, ozone is also the precursor to the OH radicals during the daytime and NO_3 radicals at night, which initiates the degradation of most atmospheric species. Ozone itself is a gas phase oxidant for various olefin organic species and a liquid phase oxidant for many sulfur species, particularly SO_2 that is converted into sulfuric acid (Seinfeld and Panis, 1998). Hence, changes in atmospheric variables can change ozone abundance and drive feedbacks through ozone. Hydrocarbons, nitrogen oxides, and sunlight dictate the production of ozone in the troposphere; the OH radical is the initiator of its production. The abundances of all these species will affect ozone production. The impact of climatological variables on OH abundance was discussed earlier. The emission of hydrocarbons is controlled by anthropogenic sources and the biosphere. The abundance of nitrogen oxides is controlled by emission (anthropogenic and natural) and production by lightning. Thus, connections of atmospheric ozone to biosphere, hydrological cycles, clouds, and temperature are evident. This is an example of how atmospheric variables and their changes can lead to a feedback in the chemical system.

OVERVIEW OF FACTORS CONTROLLING CLIMATE, CHEMISTRY, AND AEROSOL INTERACTIONS

An increase in the oxidative capacity of the troposphere will lead to changes in the rates of production and destruction of species that lead to the generation and growth of aerosols. Clearly a large fraction of the aerosol in the troposphere is produced from gas phase emissions that lead to condensable chemicals. Water and these chemicals, either by themselves or with other condensables, lead to the production of aerosol. For example, sulfate aerosol is generated by the oxidation of SO_2 to gas phase sulfuric acid, which condenses (some times with other species such as ammonia) in the presence of water vapor to produce sulfate aerosol. Therefore, an increase in OH would lead to more H_2SO_4 and hence more sulfate. Thus, there is a direct coupling between the abundances of reactive species and aerosol. One of the key factors in the formation, sustenance, and composition of the clouds is the cloud condensation nuclei that are needed. It is known through various studies that cloud condensation nuclei can be generated by aerosol, which is processed in the atmosphere. The atmospheric processing can render those unique properties needed to be a cloud condensation nucleus to an aerosol particle. Oxidants in the troposphere can alter the surface (and even the bulk) of the aerosol. For example, a hydrophobic organic aerosol (or an aerosol coated with an organic layer) can be oxidized to produce chemical functional groups that convert a hydrophobic to a hydrophilic aerosol. Hydrophilic aerosols are a key to many processes in the atmosphere, and especially for the formation of cloud condensation nuclei. Thus, changes in gas phase composition can alter the hygroscopicity of aerosols and hence the ability of aerosols to induce nucleation of droplets (i.e., cloud formation). In addition, the presence of aerosols in the atmosphere greatly alters the composition of the atmosphere because of heterogeneous and multiphase reactions that occur on or in the aerosol. The consequences of heterogeneous and multiphase reactions on the composition can be dramatic as in the case of the Antarctic ozone hole. They can also be less dramatic but extremely significant for global budgets. For example, aerosols convert active nitrogen oxides to nitric acid and hence reduce the ability of the atmosphere to photochemically generate ozone. Thus, chemical processing, coupled with the generation of aerosols in the atmosphere, couples atmospheric chemical processes with the important cloud feedback mechanism.

The biosphere interacts with the atmosphere, and these interactions have a significant impact on the climate system. A large number of the chemicals in the atmosphere originate in the biosphere. These include such gases as methane, hydrocarbons that alter the chemistry of the troposphere, and precursors to aerosols from the terrestrial regions and dimethylsulfide (DMS), methyl bromide, organics, and others from oceans. Of particular note is the emission of DMS from the oceans; such emissions have been proposed as a possible feedback on the climate system (Charlson et al., 1987; Shaw, 1983). This well-publicized feedback links the production of aerosol from dimethylsulfide oxidation and the subsequent change in the cloudiness of the planet to surface temperature and insolation, which then affect the emission of DMS from the oceans. The increased emission of DMS to the atmosphere leads to an increased sulfate aerosol production. In this hypothesis the increased sulfate production is expected to alter the properties of the clouds, which decrease the incoming solar radiation and thus cool the surface and decrease insolation. Whether such a change at the surface would increase or decrease DMS emissions was left open by Charlson et al. (1987). Such a feedback system clearly connects the temperature and insolation changes with oceanic emissions, to gas phase processes, to cloud processes, to radiation changes.

Some links in the feedback have some support, such as the seasonal correlation of cloudiness, non-sea salt sulfate and sea-to-air DMS fluxes in the Southern Hemisphere (Ayers et al., 1991; Boers et al., 1994). There is also some tentative support for a positive correlation between the sea-to-air DMS flux and surface solar radiation, suggesting that the feedback may be negative (see Chapter 8). In contrast Bates and Quinn (1997) found the DMS output in the equatorial waters to be invariant and concluded that the connection between DMS emission and atmospheric and oceanic variables remains “elusive.” In general the mechanistic understanding is far from complete. For example, the reaction pathways of DMS beyond its original reaction with OH are poorly known (Davis et al., 1999), as is the relationship between cloud droplet number and cloud condensation nuclei (Lohman et al., 1999). As discussed in Chapter 8, the processing of DMS by marine planktonic ecosystems is just beginning to be elucidated. Therefore, this hypothesis of a strong climate feedback process involving DMS is in an uncertain state.

As discussed above, the connection between gas phase oxidation to new particle formation and its coupling to cloud condensation nuclei formation is an example of the coupling between purely chemical processes and other atmospheric feedbacks.

Chemistry and Transport Interactions

The change in the abundance of the upper tropospheric reactive species because of changes in the transport processes or the increase in water vapor is another example of coupling between chemical and other atmospheric feedback processes. As the climate warms, the lapse rate and the abundance of water vapor in the upper troposphere will change (see Chapter 3). These changes will influence both the transport and mixing of chemicals to the upper troposphere and their chemical transformations in the upper troposphere.

A change in the vertical transport of reactive species that act as precursors for OH—for example acetone, methyl hydroperoxide, formaldehyde, or acetaldehyde—will enhance the chemical reactivity of the upper troposphere and increase the production of ozone in this radiatively crucial region of the atmosphere. This is especially efficient if nitrogen oxides are transported along with the other active ingredients into the upper troposphere.

Stratospheric Chemistry–Surface Climate Interactions

Changes in the stratosphere and their impact on the troposphere are also of major interest. Increases of greenhouse gases or the release of chemicals that destroy ozone in the stratosphere can produce large dynamical changes in the stratosphere that influence the surface climate. Within the stratosphere, chemical processes, radiative processes, and dynamical processes are all strongly coupled. Changes in stratospheric ozone abundances and their future levels can be altered by the changes in stratospheric temperature and water vapor, which are driven by greenhouse gases. Greenhouse warming at the surface and cooling of the stratosphere by increased carbon dioxide, methane, and water vapor may delay the expected recovery of the ozone layer, the ozone hole may persist longer, and Arctic ozone depletions may continue beyond the time currently estimated. These changes will impact the ultraviolet (UV) radiation available in the troposphere. Furthermore, the dynamical and transport consequences of the ozone changes on the troposphere can also be significant (Hartmann et al., 2000; Shindell et al., 2001; Thompson and Solomon, 2002).

Regional Climate–Air Chemistry Interactions

An impact of global climate change will be regional changes in chemical composition, UV levels, deposition rates, emission rates, precipitation rates, and other variables. Therefore, regional and urban air quality will be impacted by global climate changes superimposed on regional and local conditions. For example, changes in water vapor due to climate change will impact local and regional ozone production and the rate at which chemicals are removed from the location of emission. The global-scale changes will also alter the transport of species in and out of a given region of interest. Therefore, requirements for attainment of an air quality standard in a given region or location will be affected by climate change.

Factors That Control Chemical Feedbacks

Processes that are affected by changes in temperature, water vapor abundance, and other climate variables by means of atmospheric chemical processes are

1. gas phase oxidation processes;
2. heterogeneous and multiphase chemical processes;
3. photolytic processes;
4. transport and mixing of atmospheric constituents;
5. emissions from the terrestrial and oceanic sources that control the flux of species into the atmosphere; and
6. deposition of atmospheric degradation products and constituents that remove the chemical constituents from the atmosphere.

These processes are also affected by factors such as UV radiation, flux into the atmosphere, and flux out of the atmosphere. The representation of these processes in models is the key to the recognition and quantification of the role of feedbacks.

DEVELOPING A SCIENTIFIC STRATEGY

As discussed above, there are many chemical feedbacks in the atmosphere; most of them have been qualitatively identified and some of them have been assessed to a limited extent (i.e., the sign of the feedback is known and in some cases the magnitude is known roughly). The effects of other feedbacks discussed in this document on atmospheric chemistry feedbacks can be large and greatly alter the impact on crucial areas such as regional and urban air quality. Quantitative assessments of the effect of the feedbacks outlined in this chapter on the overall radiative balance, the surface temperature change, or some other “impact proxy” are lacking. Many of the atmospheric chemistry feedbacks are identified in principle and have been semi-quantitatively evaluated by their proponents; but reliable quantification awaits a consensus from the community that includes a more accurate treatment of the key processes and their integration into comprehensive models. The first step in dealing with climate-air chemistry feedbacks is to better understand the atmospheric processes responsible for the formation and destruction of the chemical species of interest. These processes must be understood at a sufficient level to quantitatively evaluate them. Such quantification requires detailed knowledge of the chemical processes (e.g., their rates, products, their variation with atmospheric conditions) and an accurate knowledge of the composition of the current atmosphere. Because of the spatio-temporal complexity of the climate system, the role of transport and mixing processes, and the local nature of many of the feedback processes, it is necessary to incorporate these processes in a global climate model to test their global significance and assess their local consequences. Because many of the species of interest, especially the aerosols, are highly variable in space and time, the resolution of the models has to be sufficient (e.g., 1^o x 1^o, unless processes such as convection are being explicitly simulated, which require higher resolution) to capture the nonlinearities in the processes. The representation of processes in models must be sufficiently faithful representations of nature to deal with nonlinearities in processes and their coupling to other Earth system processes. Such an advance is essential before the contribution of a feedback can be calculated.

When a sufficient fundamental understanding of the basic processes that couple air chemistry and climate is achieved, these processes should be incorporated in regional and global atmospheric climate models. These models are essential to integrate and hence quantify the key climate-chemistry feedbacks. Regional models are needed to evaluate detailed emissions-chemistry-climate interactions, and global models are needed to evaluate interactions with the atmospheric general circulation and broader Earth system.

Aerosols and their studies also deserve special attention. Although the paradigm for studying gas phase processes appears to be reasonably well established and has been reasonably successful, studies of and on aerosols are at a very early stage. Currently knowledge of the composition, surface characteristics, and their spatial and temporal variations is at best rudimentary. The processes that lead to the production of aerosols (the nucleation processes) are incapable of explaining alone the current observations of aerosol distributions. Therefore, the physical and chemical processing of aerosols, the dependence of these processes on climate, and the influence of climate-chemical interactions on the optical properties of aerosols must be elucidated. They can be done in steps (e.g., observation and understanding of how aerosols change with conditions, connecting the atmospheric conditions to climate variables, and measuring the optical properties under different conditions of temperature, humidity, and composition)

The research needs can be summarized as follows:

- A complete understanding of the emissions, atmospheric burden, and final sinks for carbonaceous aerosols needs to be developed. This class of aerosols includes a wide range of different species that are often simply characterized as organic and elemental or soot. They act as greenhouse agents, can either warm (soot) or cool (organic) the climate, and alter clouds and the hydrological cycle. To understand the role of anthropogenic activities in changing the atmospheric burden of the carbonaceous aerosols, speciated measurements of the aerosols at the emission source and in the atmosphere need to be made with the same techniques so that atmospheric burdens can be attributed to specific sources. In addition, absolutely calibrated emissions inventories need to be developed for each species of carbonaceous aerosols so that the atmospheric measurements provide a true test of the global models. This should include airborne, satellite-based, and ground-based observations. Airborne and satellite measurements have become more feasible because of improvements in instrumentation, data reduction algorithms, and input data. Reduction of existing satellite data to retrieve aerosol optical depth is being investigated.
- The processes and the global range of conditions under which carbonaceous and other aerosols can interact with the cloud and hydrological cycle need to be defined. The key atmospheric processes that influence the radiative, cloud condensation, and ice condensation properties of aerosols need to be characterized. Intensive regional measurement campaigns (on the ground, airborne, by satellite) should be mounted that are designed specifically to improve global aerosol models so that the improved knowledge of the processes can be directly applied in the predictive models that are used to assess future climate change scenarios. Better use needs to be made of the recent development of instrumentation to measure the chemical composition of aerosols, ability to measure in-situ extinction and

scattering, advances in the microphysical modeling, and availability of other ancillary input data. These characterizations should be done in concert with other field, lab, and modeling studies to improve the needed database for process understanding.

- The key processes that control the abundance of tropospheric ozone need to be quantified, including but not limited to stratospheric influx; natural and anthropogenic emissions of precursor species such as NO_x, CO, and VOC; the net export of ozone produced in biomass burning and urban plumes; and the loss of ozone at the surface. Improved characterization is required of the type and magnitude of chemistry-climate feedbacks that would lead to alteration of these processes with future climate change.
- The chemical feedbacks that can lead to changes in the atmospheric lifetime of CH_4 need to be identified and quantified (This could be defined equivalently as a measure of the global mean OH abundance) by careful integration of models and measurements; there is no clear method for deriving these feedbacks from measurements alone. These feedbacks on tropospheric OH include stratospheric ozone depletion, increasing temperatures and water vapor in a future climate, changing emissions of NO_x and CO from both natural ecosystems and anthropogenic activities, alterations in lightning production of NO_x, and of course the increasing abundance of CH_4.

7

BIOGEOCHEMICAL FEEDBACKS AND THE CARBON CYCLE

SUMMARY

Both the marine and terrestrial carbon cycles contain potentially important feedback processes. There are, however, major gaps in understanding. No definitive explanation has been given for the vast uptake of CO_2 by the terrestrial biosphere, and no confident prediction can be given of future biological uptake or release of CO_2, particularly over the long term. Few observations are available to guide the necessary scaling of vegetation-climate feedbacks from the scale of an individual leaf to a landscape mosaic of vegetation and soils. In the marine realm the strengths of a wide variety of potential feedback mechanisms involving CO_2 and DMS are yet to be determined.

Research into carbon uptake by the land and ocean as outlined in the U.S. Carbon Cycle Plan (Sarmiento and Wofsy, 1999) and North American Carbon Program (Wofsy and Harriss, 2002) should be undertaken to characterize and reduce the uncertainty associated with carbon uptake feedbacks. The Panel also recommends that research outlined in the Surface Ocean Lower Atmosphere Study (SOLAS) Science Plan be adopted in order to improve our understanding of DMS-climate feedbacks as well as carbon cycle feedbacks that involve air-sea transfer (such as iron-CO_2 feedbacks).

The U.S. Carbon Cycle Science Plan outlines a strategy to "deliver credible prediction of future atmospheric carbon dioxide levels . . . by means of approaches that can incorporate relevant interactions and feedbacks of the carbon-cycle climate system." The plan advocates strong multiagency collaboration to carry out specific program elements, which include (1) expanded, long-term observational networks in the atmosphere, ocean and terrestrial systems; (2) historical reconstructions of CO_2 emissions and terrestrial carbon inventories; (3) intensive ocean and land process studies; and (4) modeling and synthesis, including the development of models that

couple the carbon cycle to the rest of the climate system. SOLAS is an international research initiative designed to "achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere, and of how this coupled system affects and is affected by climate and environmental change." To achieve this goal the SOLAS Science Plan recommends increased cooperation between atmospheric and marine scientists in order to develop process studies, monitoring programs, process-level models, and Earth-system models.

As greenhouse gases increase in the atmosphere and warming is produced, the net exchange of carbon between the atmosphere and reservoirs of carbon in the land and ocean may be altered. Temperature and precipitation changes may alter the uptake of carbon by plants. Increased temperature in high latitudes may change the storage of carbon by frozen soils and associated biomass. Changes in ocean temperature and circulation may alter the storage of carbon in the ocean. All these potential feedback processes will alter the amount of atmospheric carbon dioxide increase that results from fossil fuel combustion by humans. The production and uptake of other radiatively active gases in the land and ocean may also be modified as a result of climate change.

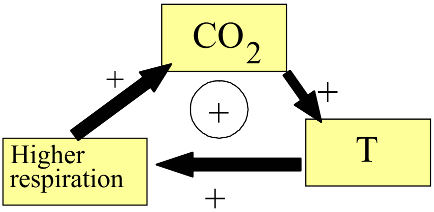
The land and ocean currently exchange approximately 120 and 90 petagrams of carbon per year with the atmosphere, respectively (Prentice et al., 2001). Although the ocean constitutes a much larger reservoir of carbon than the land biosphere, both land and ocean carbon exchanges are important for understanding the anthropogenic effect on atmospheric carbon dioxide. Both land and ocean also have the potential to produce feedbacks between climate change and uptake of anthropogenic carbon.

The quantities of carbon stored as plant biomass and soil organic matter on land, or carbonate species and organic carbon in the sea, vastly exceed CO_2 in the atmosphere. Analysis of long-term changes in atmospheric CO_2, $^{13}CO_2/^{12}CO_2$, and O_2 show that the atmospheric increase in CO_2 was less than half of the fossil fuel input between 1991 and 1997, with the remainder approximately equally partitioned among the land and ocean (Battle et al., 2000).

TERRESTRIAL CARBON FEEDBACKS

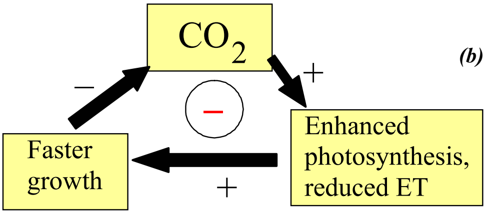
Climate—Plant—CO_2 Feedbacks

Atmospheric CO_2 is regulated by complex processes involving terrestrial and marine plants, which fix inorganic carbon as organic matter, heterotrophic organisms that mineralize organic matter back to CO_2, and a variety of geochemical and biogeochemical processes that convert CO_2 to and from mineral carbonates (e.g., $CaCO_3$). All of these processes are sensitive to climate. Nevertheless, assessments of climate change have long regarded feedbacks in the carbon-climate system as basically simple two-step processes, as depicted in Figure 7.1 for the terrestrial biosphere:



Conventional views of CO_2-climate feedbacks.

(a) *Temperature(T)-respiration feedback.* Terrestrial systems respond to climate warming by increasing respiration, adding CO_2 to the atmosphere from stocks of soil organic matter, increasing CO_2, and enhancing warming.



(b) *CO_2-growth feedback.* Plants increase rates of photosynthesis when grown at elevated concentrations of CO_2, especially in dry climates or in nutrient-rich soils where other factors do not inhibit the response to CO_2. Evapotrasporation (ET) is reduced, lowering the water requirement for vegetation.

FIGURE 7.1 Climate-land biosphere feedback processes: Conventional view.

The positive feedback loop (*a*) is based on the increased rate of respiration observed for almost all organisms as temperatures increase. This factor underlies the paradoxical distribution of soil organic matter with latitude. Rates of production of organic matter are slower in cold versus warm climates, but rates of decomposition decline faster than production. Huge stocks of organic carbon, several times larger than the quantity of CO_2

in the atmosphere, are locked up in the soils of boreal and sub-boreal regions, and feedback (*a*) could thus have a major impact on future levels of CO_2.

The negative feedback (*b*), plant growth accelerated by CO_2, is also a well-known biophysical process. Green plants all use the enzyme rubisco to bind CO_2 during photosynthesis. Rubisco takes carbon dioxide and attaches it to ribulose bisphosphate, a small sugar with five carbon atoms; then it cuts the molecule into two identical pieces with three carbon atoms. In spite of its central role rubisco is remarkably inefficient. Typical enzymes process 1,000 molecules s^{-1}, but rubisco fixes only about three carbon dioxide molecules per second. High concentrations of CO_2 (roughly 260 ppm) are needed to bind with the enzyme in a cell. Plants compensate for the inefficiency by allocating substantial resources to rubisco, and most plants must allow rapid gas exchange with the interior tissues of the leaf to provide the needed high concentrations of CO_2. This circulation, through opening of the stomates of the leaf, allows water loss by evaporation. Elevated CO_2 thus allows plants to increase growth with fixed (or reduced) allocation to rubisco and with lower requirements for water.

The CO_2-growth feedback modifies the quantity of atmospheric CO_2 by altering the amount of organic matter in living biomass and the inputs of fresh organic matter to soils, in contrast to the respiration feedback that alters the quantity of dead organic matter in soils, much of which is old and recalcitrant. The stocks of biomass and short-lived organic matter that may be maintained on the land impose the limit for the CO_2-growth feedback. These stocks are subject to manipulation by harvesting, preservation of wood and paper, and other management. The limit on the temperature-respiration feedback is imposed by the available stores of soil organic matter, generally assumed to be larger than potential biomass stocks.

Real ecosystems do not however behave just like simple organisms exposed to a single, instantaneous change in the environment. For example, some ecosystems show quite small stimulation by elevated CO_2, and responses typically decline during extended studies. Several factors are at work. Stomates may remain open despite higher CO_2, to restrain the rise in leaf temperature; moreover, reduced water use provides little help to plants in well-watered environments. Other resources, such as nutrients (N, P, Ca, K), often limit plant growth, inhibiting any stimulation by CO_2 (Bauer et al., 2001).

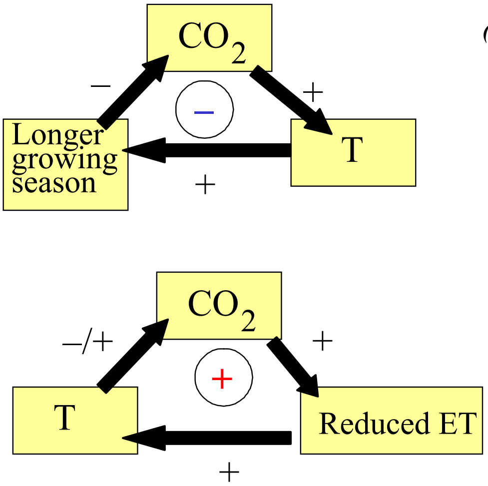
Some critically important feedbacks occur only on long time scales. For example, the length of the growing season has been shown to provide the dominant effect of climate on carbon sequestration by mid-latitude forests. Years with warm temperatures in spring have greater net uptake of CO_2 than cold years (Barford et al., 2001). Greater rates of growth and carbon uptake are observed for mid-succession forests in warmer parts of the temperate zone. These effects far exceed any increase in respiration, contradicting expectations of the temperature-CO_2 feedback (*a*).

The peatlands of Alaska, Canada, and Siberia represent a very important, potentially positive, feedback between CO_2 and climate (Chapin et al., 2000). Enormous quantities of carbon have accumulated as peat since the end of the last ice age, equivalent to 200 ppm or more of atmospheric CO_2 (Gorham, 1991). Peat is preserved by being saturated with water, maintained in the low-precipitation boreal environment by very slow evaporation, or by being frozen. Peatlands that become drier are subject to fairly rapid oxidation, either by microbial activity or by natural fires (Goulden et al., 1998; Harden et al., 2000). Evidence suggests that this process is occurring at present, and it could accelerate markedly according to some climate scenarios. The key lies in future changes in regional precipitation at least as much as with temperature.

Figure 7.2 illustrates two of the feedbacks between the climate system and the terrestrial system. The same interactions viewed at the landscape scale and long times may have strong feedbacks opposite to those inferred for single organisms subjected to instantaneous perturbations of a single environmental variable (*cf.* Fig. 7.1).

A Scientific Strategy for Terrestrial Carbon Feedbacks

There is currently no definitive explanation for the vast uptake of CO_2 by the terrestrial biosphere, nor is there a confident prediction of future uptake or release of CO_2 from the terrestrial biosphere. The major issue is to determine the responses of whole ecosystems and landscapes to the full diversity of environmental changes attending climate change. Warming per se is likely less important than other factors, such as precipitation, evaporation, humidity, cloudiness, CO_2 concentrations, land use, and land management. Physiological processes responsible for vegetation-climate feedbacks that operate at the scale of an individual leaf need to be scaled to a canopy of leaves and then to a landscape of thousands of plants. There are few observations to guide this scaling, as most studies of stomatal conductance and its response to CO_2 are obtained from leaf measurements. In addition, most studies examine the short-term response of plants to CO_2. Longer-term acclimation to high CO_2 will change the short-term reduction in stomatal conductance.



System interactive CO_2-climate feedbacks.

(a) ***Temperature (T)-respiration feedback.*** Terrestrial systems respond to climate warming by increasing growth due to longer growing seasons, removing CO_2 from the atmosphere and storing in biomass and fresh organic matter.

(b) ***CO_2–growth feedback.*** Evapotranspiration (ET) is reduced, lowering latent heat fluxes and increasing climate warming through reduced cloud cover and increased sensible heat

FIGURE 7.2 Climate-land biosphere feedbacks: System interactive views.

The key to understanding the terrestrial biosphere's uptake of CO_2 is to undertake observations and analysis at large spatial scales for extended times. These observations should integrate measurements of the carbon cycle with measurements of the energy and water cycles. The Panel supports the strategy of the U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999) and the North American Carbon Program (Wofsy and Harriss, 2002) in this regard. For the purposes of this report the Panel supports the U.S. Carbon Cycle Science Plan's focus on the following two questions:

1. What has happened to the carbon dioxide that has already been emitted by human activities?
2. What will be the future atmospheric CO_2 concentration trajectory resulting from both past and future emissions?

These fundamental questions were articulated into six specific goals, two of which focus on the terrestrial carbon cycle.

1. Quantify and understand the Northern Hemisphere terrestrial carbon sink.

2. Determine the impacts of past and current disturbance, both natural (e.g., boreal fires) and anthropogenic (e.g., land use) on the carbon budget.

These goals are considered to be feasible steps over the next five or so years to address uncertainties in the carbon cycle and interactions with climate change. The focus on North America is intended as a first step to define global feedbacks involving CO_2 and climate. Implementation of these goals has been laid out in plans for the North American Carbon Program (NACP) (Wofsy and Harriss, 2002). The NACP includes radically new networks of long-term atmospheric observations and ecosystem studies. Data assimilation systems are described that for the first time would allow us to combine these data with high-resolution assimilated winds to define CO_2 net exchange at landscape and continental scales. The plan also prescribes extensive manipulations and field measurements to elucidate the factors regulating CO_2 uptake or release by major ecosystems. Thus, the NACP represents a systematic effort to address the carbon-climate feedbacks at the time and space scales relevant for understanding the mutual interactions of the carbon cycle and the climate system. This program, if implemented, would provide the basic information and analytical framework needed to quantify and understand climate-carbon feedbacks for North America, and it would provide the template for extension to other major land masses. In addition to the goals outlined above, the NACP will also be concerned with emissions of CO_2, CH_4, and CO. (Improving accounting of carbon emissions and uptake is also important for reasons other than the objectives of this report; they are vital for developing and maintaining effective greenhouse gas mitigation policies.)

Previous carbon cycle research largely focused on studies of single components, such as the atmosphere or ocean, or through small-scale process studies. But carbon is exchanged continuously through the atmosphere, land biosphere, soils, and oceans. The temporal and spatial scales of the program must be appropriately large for addressing climatic issues, and data and models from all components must be brought together to develop information on global carbon balances. Results must be scaled up from process studies and inventories and rigorously compared to information gained at a regional or continental scale. These integration objectives are shared by and are embodied in the program's major elements for integration, including innovative new assimilation and data fusion systems that bring together diverse data and models, linking information at various scales to provide a consistent continental-scale carbon balance, resolved temporally by season. This coordination of science activities requires similar coordination among agencies involved in implementation.

Major Program Elements of the Carbon Measurement and Analysis Strategy

Long-term atmospheric measurements of the carbon budget are required from the ground, aircraft, and satellites, which should provide spatially and temporally resolved, three-dimensional atmospheric data for the major carbon gases, CO_2 CH_4, and CO, to enable reliable estimates for North American sources and sinks of these gases. These observations are required to obtain regional and continental sources and sinks for atmospheric CO_2, CH_4, and CO. The network planned by NACP extends present remote monitoring networks (Tans et al., 1996) of atmospheric observations to provide dense coverage and vertical soundings in the interior of the continent. Present networks of flux stations (Baldocchi et al., 2001) will be enhanced to provide traceable absolutely calibrated concentrations, and coverage will be extended to include many more representative regions.

Intensive field programs that are planned by NACP, including large-scale airborne and field campaigns, should be launched to provide datasets to evaluate and to improve the design of atmospheric and surface measurement networks, to develop and test models, to interpret observations, and to provide atmospheric snapshots to constrain fluxes. These efforts should provide continuous feedback on uncertainties in modeling and assessment tools for carbon accounting.

Inventories of carbon in major ecotones (e.g., the Forest Inventory Analysis [Goodale et al., 2002]) will need to be enhanced to encompass full carbon accounting and complemented by remote sensing and models to provide a complete carbon budget for the land. Lands (peatlands, scrub land, suburban landscapes) and carbon pools (roots, coarse woody debris, shrubs) not currently inventoried must be included. A hierarchical conceptual approach is planned in the NACP to support a multiscale interpretation, with intensive studies providing access to details and mechanisms that are extended using remote sensing, extensive inventories, and mechanistic models and join the atmospheric and ocean studies as components in a unified analysis framework.

As outlined in several other disciplinary chapters of this report, the integration of models and model-data assimilation will be important. Such efforts could provide knowledge of the atmospheric concentrations of CO_2 over the entire continent and adjacent waters at frequent intervals. We support the flow of information and the integration outlined by the NACP to obtain regional carbon accounting (see Figure 7.3).

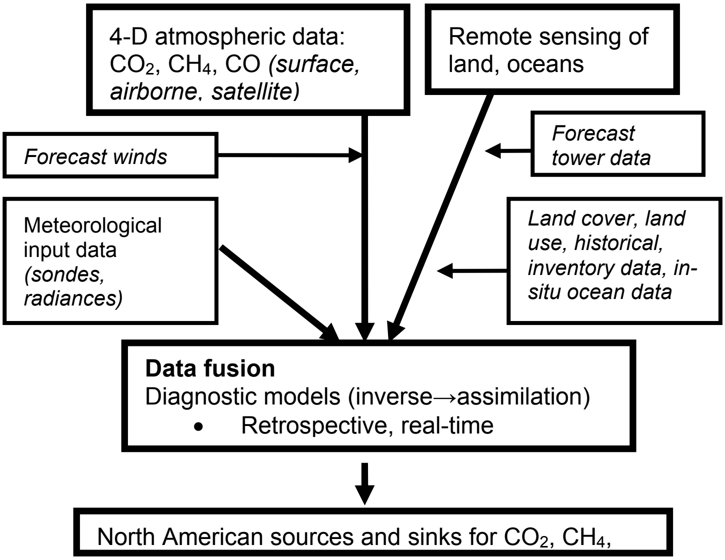


FIGURE 7.3 Data flow and integration in the NACP. Complexity and level of synthesis increase down the figure. Valuable data products are delivered at each level. Note the central role played by the model-data fusion systems that combine observations from diverse sources, using data-driven models and advanced data assimilation and optimization methods.

A critical step will be to develop new classes of diagnostic models to determine sources and sinks of CO_2 and other gases. Data-driven models of carbon dynamics in vegetation and soils will be combined in a data fusion framework with high-resolution meteorological information, surface flux data, and atmospheric concentrations to derive fluxes and a quantitative representation of the state of the atmosphere and of the carbon cycle.

The Panel recommends that the NACP be implemented with major initiatives in the aforementioned key areas. We also support its plans for regular state-of-the-art assessments of carbon cycle science and carbon inventories for North America, with eventual extension of the observations and analysis framework to the entire globe. Linkage to the Global Carbon Project (<http://www.globalcarbonproject.org>) of the International Geosphere-Biosphere Programme (IGBP), World Climate Research Programme (WCRP), and International Human Dimensions Programme on Global Environmental Change (IHDP) would be useful in this regard.

MARINE BIOGEOCHEMICAL FEEDBACKS

Marine carbon feedbacks have been evaluated almost exclusively with models. This is unfortunate because the marine carbon cycle models being used for climate change studies are not capturing processes that may be key elements of feedback mechanisms. This is particularly true for the biological component of the models. The most advanced marine carbon cycle model that has been used in climate change simulations (Cox et al., 2000) does not include, for example, multiple phytoplankton species, iron limitation, nitrogen fixation, variable carbon-to-nitrogen ratios, and dissolved organic matter, all of which appear to be important features of the marine carbon cycle. Most other models used for such purposes are even simpler. The reasons for these omissions are various, but they include the lack of data for developing defendable parameterizations as well as the additional computational expense of increasing the complexity of the models.

Models nevertheless can help to put rough boundaries on the strength of various feedback mechanisms. In terms of the overall feedback of the marine carbon cycle on climate on the time scale of a century, the models vary from showing almost no impact on ocean carbon uptake (Joos et al., 1999; Maier-Reimer et al., 1996) to a reduction of about 10-15 percent (Friedlingstein et al., 2001; Matear and Hirst, 1999; Sarmiento et al., 1999;). This overall effect represents the sum of individual feedbacks that may be considerably larger. Some of the potentially important marine biogeochemical feedbacks are described briefly below.

Physical and Chemical Feedbacks on Atmospheric CO_2

Solubility–Temperature Feedback

The solubility of CO_2 and the degree to which it reacts to form other inorganic and nonvolatile forms of carbon decreases with increasing temperature with an accurately known functionality that is described by temperature-dependent equilibrium constants. Thus, there is a positive feedback on atmospheric CO_2 associated with temperature changes and the inorganic chemistry of CO_2 in seawater. The few modeling studies of this feedback regard it to be of modest strength, amounting to a 10-15 percent reduction of the cumulative anthropogenic CO_2 uptake by the ocean on the century time scale (Joos et al., 1999; Matear and Hirst, 1999; Sarmiento et al., 1999).

CO_2 Uptake–Ventilation Feedback

In order for substantial carbon to be taken up by the oceans, it must be first moved across the air-sea interface and then from the surface ocean to deeper in the ocean. The resistance of the air-sea interface is relatively small, and so it is largely the vertical circulation in the ocean, including the ventilation of the thermocline and the formation of intermediate and deepwaters, that regulates the uptake of anthropogenic CO_2 by the ocean. As noted in Chapter 5 some models predict that the rate of overturning by the thermohaline circulation will decrease in a warmed world, which would result in a positive feedback on atmospheric CO_2. The few studies on this feedback are in disagreement with regard to its strength, varying between essentially no impact on ocean carbon uptake (Maier-Reimer et al., 1996) to as much as 17 percent (Sarmiento et al., 1999). Differences are primarily due to the sensitivity of the ocean circulation to CO_2 changes. This underscores the point that marine carbon cycle models are only as good as the circulation models in which they are embedded.

Stratification–CO_2 Mixing Feedback

As discussed above, many models predict changes in ocean circulation, which can alter the CO_2 balance of surface waters and therefore atmospheric CO_2. For example, stratification of high-latitude waters would inhibit the upward flux of deepwaters, which are enriched in CO_2 due to the decomposition of organic matter sinking from the upper ocean, resulting in a negative feedback on atmospheric CO_2. This would be counteracted to some degree by a reduction in carbon export from surface waters due to the reduced upward flux of nutrients. For example, Bopp et al. (2001) found this effect to dominate the 6 percent decrease in carbon export from surface waters for a CO_2 doubling in their models. The few studies on the overall feedback disagree with regard to its strength, though they generally agree that this feedback tends to have a similar magnitude (but opposite in sign) to the CO_2 uptake-ventilation feedback described above (Joos et al., 1999; Matear and Hirst, 1999; Sarmiento et al., 1999).

ENSO–CO_2-Upwelling Feedback

A similar feedback may operate in low latitudes, as indicated by some models that predict increased frequency of El Niño events with increased

CO_2 (Timmerman et al., 1999). Such an increase would reduce the natural marine source of CO_2 to the atmosphere (due to upwelling), creating a negative feedback on atmospheric CO_2. Other models show a reduction in equatorial upwelling, which would have a similar effect (Bopp et al., 2001). This feedback has not been quantified, though at least one modeling study suggests that the equatorial Pacific does not exert a strong control on atmospheric CO_2 on the century time scale (Sarmiento and Orr, 1991). However, the relative roles of high and low latitudes in regulating atmospheric CO_2 are active areas of research (Broecker et al., 1999).

Overview of Biological Feedbacks on Atmospheric CO_2

Carbon Export–Temperature Feedback

Phytoplankton growth rates generally increase with temperature (Eppley, 1972) and so the potential for a negative feedback exists. The fraction of photosynthetically derived material that is exported to deeper waters, however, is suggested by a recent synthesis of many field studies to decrease with increasing temperature (Laws et al., 2000), which would constitute a positive feedback. Bopp et al. (2001) found very little sensitivity of carbon export to climate warming using a simple ecosystem model. That model, however, did not include the findings of Laws et al. (2000), and so this feedback remains poorly quantified; even its sign is not known.

Carbon Export–Light Feedback

The exposure of phytoplankton to light depends on the surface irradiance, the opacity of the water column and the depth of the mixed layer (deeper mixed layers result in more time that phytoplankton spend in the dark). Changes in cloudiness could therefore change photosynthesis. The opacity of the water column is largely due to changes in phytoplankton abundance but also to colored dissolved organic matter, the dynamics of which are poorly understood. Finally, many climate models (e.g., Bopp et al., 2001) predict shallower mixed layers due to decreases in surface density, which could enhance light levels and therefore photosynthesis. Bopp et al. (2001), the only study to quantify this feedback, found increases in carbon export of as much as 20 percent over large regions of the high latitudes due to decreases in mixed layer depth induced by a CO_2 doubling.

Carbon Export–Iron Input Feedback

Phytoplankton growth in many parts of the ocean is limited by the availability of iron, a substantial fraction of which is derived from wind-blown continental dust (Martin et al., 1991). Thus, climate-induced changes in continental aridity, wind speed, and wind direction may influence phytoplankton production. Ice core data, which show higher levels of atmospheric dust during glacial times, suggests that iron may be part of a positive feedback loop (Martin, 1990). This feedback has not been quantified using models because the incorporation of iron into marine ecosystem models is just beginning (Moore et al., 2002). Many questions remain about how and in what form iron is delivered to the ocean, how it is made available to phytoplankton and how it is cycled in the marine ecosystem.

CO_2–Calcification Feedback

The calcification rates of coccolithophores and coral reefs have recently been shown to decrease with increasing atmospheric CO_2 (Kleypas et al., 1999; Riebesell et al., 2000). Because calcification is a source of CO_2, such organisms are potentially part of a negative feedback on anthropogenic CO_2. Using a simple model, Zondervan et al. (2001) suggest that this feedback is rather small for the coccolithophores, which dominate global calcification.

Feedbacks Involving Dimethylsulfide

Dimethylsulfide (DMS) is thought to be a major precursor of cloud condensation nuclei in unpolluted air (see Chapter 7); therefore the release of DMS from the ocean may influence cloud albedo and climate. Phytoplankton, bacteria, and zooplankton all play important roles in marine DMS cycling, so any change to the marine ecosystem as a result of climate change is likely to affect the DMS concentration in seawater and hence its flux to the atmosphere. The turnover of DMS in the ocean mixed layer is so rapid that the flux to the atmosphere is only a small residual of much larger fluxes. Thus, modest changes in internal cycling have the potential of producing large changes in the air-sea flux. However, because the response of marine ecosystems to climate change is uncertain, the response of marine DMS emissions is also uncertain. Additional uncertainty is caused by production of the DMS precursor, dimethylsulfoniopropionate (DMSP), which varies greatly among phytoplankton species (Keller et al., 1989). Zooplankton play a role in DMS cycling through grazing, which is an important mechanism for releasing DMSP from phytoplankton cells (Dacey and Wakeham, 1986). The bacterial impact on DMS cycling is through the effect on DMS yield during DMSP consumption, as well as through the direct consumption of DMS (Kiene and Bates, 1990). A significant sink of DMS also occurs through abiotic photochemical consumption (Kieber et al., 1996). These points underscore the complexity of DMS cycling in seawater and the difficulty in predicting its response to climate change.

It is not surprising that there is no simple relationship between DMS concentration and temperature, salinity or chlorophyll, as revealed by a recent synthesis of over 15,000 measurements by Kettle et al. (1999). However, DMS flux tends to increase with increasing solar radiation (Bates et al., 1987), with seasonal maxima in flux and concentration occurring in the summer (Kettle et al., 1999; Kettle and Andreae, 2000). Simó and Pedros-Alió (1999) suggest that this relationship is due to photo-inhibitory effects on bacteria (which consume DMS and reduce the DMS yield from DMSP) during conditions of high light and shallow mixed layer depth. Thus there is some support for the hypothesis of a negative feedback on the climate system involving DMS and sunlight (Charlson et al., 1987; Shaw, 1983). However the magnitude of the feedback is not known nor is the underlying mechanism well elucidated.

Ice core data provide additional insights regarding DMS-climate feedbacks. Ice core records of methanesulfonate (MSA), an atmospheric oxidation product of DMS, show that its atmospheric concentration during glacial times was substantially different compared to the present. Glacial concentrations were higher in the Southern Hemisphere (Legrand et al., 1991) and lower in the Northern Hemisphere (Saltzman et al., 1997), suggesting that the sign of the feedback may vary with location.

There have been a few modeling studies that have attempted to quantify DMS-climate feedbacks. The empirical model of Lawrence (1993) suggested that a CO_2-induced warming could be reduced by 10 percent to 50 percent due a DMS-climate (negative) feedback. Gabric et al. (1998) applied temperature and wind speed changes from a doubled-CO_2 climate model to an ecosystem model with DMS dynamics in the Southern Ocean. They found a modest (2-8 percent) increase in the flux of DMS to the atmosphere due to an increase in the gas transfer velocity and phytoplankton growth rate, both of which increase with temperature (wind speeds actually decreased slightly in the simulation). This study also supports the potential of a negative feedback, albeit a weak one. In light of the complexity of DMS cycling, these models are extreme simplifications, but they nevertheless provide a framework for attempting to quantify DMS feedbacks.

Feedbacks Involving Methane and Nitrous Oxide

The emission of methane and nitrous oxide from the ocean currently constitutes a very small fraction of the total greenhouse gas forcing of the atmosphere, however, there is the potential of large releases of these gases. Abundant reservoirs of methane are stored in ocean sediments in the form of clathrates, which are nonvolatile. Warming could release the methane into the water column and atmosphere, providing a positive feedback. This feedback has not been quantified, though the paleoclimate record suggests that the feedback may have been activated many times in the past (Bains et al., 1999). The volume of methane available for release is poorly known (Gornitz and Fung, 1994). One modeling study suggests an upper limit of 10 percent to 25 percent increase in warming over the next century due to this feedback (Harvey and Huang, 1995).

Nitrous oxide is formed in the ocean during respiration, and the rate of release appears to be a function of the dissolved oxygen concentration (Law and Owens, 1990), particularly at low oxygen levels. Because both respiration and oxygen abundance are sensitive to climate change, there is the potential for climate feedbacks involving marine N_2O. This is particularly true given the fact that the amount of N_2O release is only a small fraction of the total cycling of nitrogen.

A Scientific Strategy for Marine Biogeochemical Feedbacks

Marine biogeochemical feedbacks are to a large extent unquantified. First order questions related to even the sign of certain feedbacks exist in some cases.

The rate at which the ocean takes up carbon will very likely continue to increase because of the increasing atmospheric CO_2 level. Changes in ocean carbon dynamics driven by changes in circulation and biology will modulate this increase. The degree of this modulation is very poorly known due to large uncertainties in the projections of future changes in ocean circulation and of the response of ocean biota to these ocean circulation changes. While primary production is important for evaluating the overall intensity of carbon cycling in surface waters, it is the exported fraction (from surface waters) of primary production that is important to surface ocean and atmospheric CO_2 levels. Our ability to quantify export and its variability on large scales is improving, but it is still poor. The rate of decomposition of organic matter exported from surface waters is also very important but even more poorly known.

The feedback between marine DMS emissions and cloud albedo is potentially very large. Over the past 15 years substantial progress has been made in evaluating the mechanisms of ocean DMS cycling, including its production, consumption, release to the atmosphere, oxidation in the atmosphere, and contribution to the cloud condensation nuclei (CCN) pool. However, the nature of the overall feedback has remained elusive. The ocean is currently a minor source of methane and nitrous oxide to the atmosphere. However, there is a poorly understood potential for a large release of these gases to the atmosphere. Marine sedimentary clathrates are a very large reservoir of methane that could be abruptly released. Large amounts of nitrogen are cycled in the marine environment and the fraction released as N_2O is currently small, but the controls on this fraction are poorly understood.

Observations for Improving Understanding and Models

The main areas that deserve attention in the context of marine biogeochemistry and climate are the rate of CO_2 uptake by the ocean and the release of DMS from the ocean. If ocean circulation and biology do not change in the future, these rates can be projected with relatively high accuracy. Model uncertainties exist because we do not know to what extent changes in ocean physics and biology will modulate the cycling of carbon and sulfur in the sea. Thus concerted studies need to be undertaken to assess the response of the marine carbon and sulfur cycles to changes in ocean circulation and other climate variables, such as solar radiation and temperature. This will be best achieved by monitoring the ocean carbon and sulfur cycles over time scales ranging from months to decades. The annual cycle in ocean physical properties and other climate variables represents the major temporal forcing on marine biogeochemical systems and should be monitored intensively. Interannual and decadal climate variations represent another major forcing that needs to be understood in terms of feedbacks on the marine carbon and sulfur cycles.

Four observing system components are selected for special attention;

1. *Continued satellite-based monitoring of ocean color is needed to derive information about changes in plankton biomass and CO_2 fixation.*

2. Expanded monitoring of the atmospheric oxygen-nitrogen ratio and atmospheric DMS concentration is needed to derive information about seasonal and interannual variations in the CO_2 *fixation and export to the ocean interior and sea-to-air DMS flux, respectively, on basin-wide scales.*

3. High-resolution (monthly) time-series measurements are needed of the carbonate system (e.g., CO_2 *concentration and dissolved inorganic carbon), nutrients, oxygen, chlorophyll, dissolved organic carbon, primary production, vertical fluxes of carbon, and the main sulfur pools (particulate and dissolved DMS and DMSP) at a wide variety of ocean locations. Currently, open ocean time-series measurements are limited to the carbon cycle at a few sites, mainly in the subtropical oceans.*

4. Periodic surveys of ocean chemical and physical properties are needed to evaluate the uptake and processing of carbon in the marine environment. There have been a few such surveys in the past, including the Geochemical Ocean Sections Study (GEOSECS) of the 1970s and the WOCE Joint Global Ocean Flux Study (JGOFS) CO_2 *survey of the 1990s, and it is critical that they occur every five to ten years.*

These measurements should be made through a combination of autonomous buoys to derive temporally continuous time series; ship-based measurements to produce spatially extensive repeat surveys; and remote sensing.

In addition to these observational strategies, increased efforts are needed to develop new technologies for measuring carbon and sulfur fluxes in the sea, particularly the air-sea flux of CO_2, the sinking flux of organic carbon, the rate at which organic matter decomposes (respiration), and production and consumption of DMS and DMSP.

The primary obstacle to making projections about the marine carbon and sulfur cycles is the lack of observations to inform the models. The aforementioned observations will be critical in helping to provide adequate descriptions of the relevant processes, which can lead to refined and observationally tested model representations. The transition between observation and the development and testing of corresponding model representations of the key processes should be a seamless one; we advocate facilitating this by incorporating numerical modeling into field studies during the development and execution as well as in the data synthesis phase.

Evaluating Progress

Factors critical to the uptake of carbon by the ocean that might be derivable from observations and that can be used to test models include the following.

1. *The change in surface* pCO_2 *for a given change in temperature or the change in inorganic carbon content for a given change in heat content.* This is necessary to evaluate the solubility-temperature feedback.
2. *Change in inorganic carbon inventory for a given change in ocean ventilation rate.* This will allow the circulation-uptake feedback to be assessed. The ventilation rate can be estimated from various tracers of ocean circulation, such as chlorofluorocarbons.
3. *Change in export production and surface nutrient concentration for a given change in stratification.* This will allow the stratification-CO_2-mixing and stratification-production feedbacks to be assessed. Export production can be crudely estimated on large scales from satellites and variations in atmospheric oxygen.
4. *Change in export production for given changes in temperature, light, and iron dust inputs.* This will allow the feedbacks between carbon export and various controls on it to be assessed. Iron dust inputs on large scales can be crudely estimated from precipitation and aerosol fields derived from satellites.
5. *Change in cloud fraction and albedo for given changes in surface ocean DMS.* This will allow feedbacks involving DMS and climate to be assessed in a crude sense. Monitoring at a more detailed level (e.g., MSA, CCN densities, wind speed, SST, DMS community production) would be valuable as well.
6. *Changes in concentrations of the isotopes of methane in the atmosphere and select areas of the ocean for given changes in ocean temperature.* This would allow for feedbacks between warming and release of methane from clathrates to be assessed.
7. *Changes in the concentrations of the isotopes of nitrous oxide in the atmosphere and select areas of the ocean for given changes in a variety of ocean physical and biological properties, including stratification, temperature, and primary production.* This would allow feedbacks related to N_2O release from the ocean to be evaluated.

Programmatic Efforts

The U.S. Global Change Research Program has developed an interagency Carbon Cycle Science Program[1] with a Science Plan[2] whose goal is specifically to reduce uncertainties in understanding the carbon cycle. In addition, as part of a new international initiative the fledgling U.S. Surface Ocean Lower Atmosphere Study (SOLAS)[3] has a mission to "achieve a quantitative understanding of the key biogeochemical-physical interactions between ocean and atmosphere, and of how this coupled system affects and is affected by climate and environmental change." To a large extent a successful approach toward improving understanding and modeling of biogeochemical feedbacks is directly linked to the success of these programs. *We recommend that agencies work to ensure that the goals of the U.S. Carbon Cycle Science Program and SOLAS are met through adequate and sustained funding. These agencies should continue to ensure that U.S. Carbon Cycle Science Program and SOLAS activities fit within the framework of international activities.*

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[1] http://www.carboncyclescience.gov

[2] http://www.carboncyclescience.gov/PDF/sciplan/ccsp.pdf

[3] http://www.aoml.noaa.gov/ocd/solas/

8

MODES OF VARIABILITY

SUMMARY

Radiatively induced greenhouse warming is not the only effect of the buildup of greenhouse gases. There is a growing body of evidence that suggests that human activities may also be capable of changing the time averaged states of the natural modes of variability of the climate system, most notably the El Niño-Southern Oscillation (ENSO) and the high-latitude Northern and Southern Hemisphere annular modes. An understanding of these modes and how they react to anthropogenic forcing is essential for detection and attribution of global climate change and for interpreting the role of feedbacks. The natural variability of these modes on the year-to-year time scale provides a testbed for model parameterizations of feedbacks.

The planetary-scale atmospheric circulation exhibits preferred modes of month-to-month and year-to-year variability that exert a strong influence on regional climate and may be capable of influencing climate sensitivity. The most important of these modes are

- ENSO, which modulates the mean tropical tropospheric temperature (Angell, 1988; Newell and Weare, 1976; NRC, 2000a), the mean rainfall and vegetation over the tropical continents, and mean rate of increase of atmospheric carbon dioxide (Keeling and Revelle, 1985, Prentice et al., 2001); and
- the Northern and Southern Hemisphere annular modes, which modulate temperature, precipitation and winds, and high-latitude stratospheric ozone concentrations (Hurrell, 1995), and sea-ice concentrations (Rigor et al., 2002).

These planetary-scale modes appear to have exhibited secular trends during the past few decades. Two very strong El Niño events have occurred since 1980 and barometric pressure has tended to be above normal on the western side of the tropical Pacific, indicative of the warm polarity of the ENSO cycle, which favors reduced upwelling in the equatorial Pacific and abnormally dry conditions over its tropical continents. The ENSO cycle has exhibited a bias toward the warm polarity from 1977 onward. The annular modes in both hemispheres have exhibited trends toward the high-index polarity, characterized by below normal sea-level pressure over the polar cap regions, westerly wind anomalies at subarctic latitudes, above normal winter temperatures over most of Eurasia, a thinning of the springtime stratospheric ozone layer, and a thinning and enhanced summer melting of Arctic sea ice (Wallace and Thompson, 2001).

Whether these trends are secular in nature or merely a reflection of decadal-to-century-scale climate variability remains to be seen. In any case they have been large enough over the past few decades to significantly impact the statistics that are commonly used to assess the extent of global climate change. For example, analyses indicate that there have been substantial average increases in precipitation over the tropical oceans since the late 1970s related to increasing frequency and intensity of El Niño events (Trenberth et al., 2002). The cooling over the Antarctic continent and the rapid warming over the Antarctic peninsula is largely a consequence of the trend in the Southern Hemisphere annular mode (Thompson and Solomon, 2002). Much of the wintertime warming over the Eurasian continent, the thinning of the stratospheric ozone layer, and the retreat of Arctic sea ice is a consequence of the trend in the Northern Hemisphere annular mode (Wallace and Thompson, 2001). An awareness of these modes and an understanding of their behavior is essential for a proper attribution of the observed climatic changes in studies of climate sensitivity. For example, in diagnosing ice-albedo feedbacks it is important to know whether the observed retreat and thinning of sea ice from the 1980s to the 1990s (Rothrock et al., 1999) was a direct thermodynamic consequence of global warming, or whether it was due to the enhanced cyclonic circulation around the periphery of the Arctic observed in association with the trend toward the high-index polarity of the Northern Hemisphere annular mode (Rigor et al., 2002). In a similar manner ENSO-induced changes in the tropics need to be taken into account in diagnosing cloud, water vapor, and static stability feedbacks

It has been proposed that the observed trends in ENSO and the annular modes may be anthropogenically induced. The former may be the result of cloud-albedo feedback and enhanced warming in the eastern equatorial Pacific (Timmermann et al., 1999, Meehl and Washington, 1996). The latter may be the result of either the destruction of stratospheric ozone by

Chlorofluorocarbons (CFC's) (Volodin and Galin, 1999) or by high-latitude stratospheric cooling induced by the buildup of greenhouse gases (Shindell et al., 1999), or by some combination of the two. If these hypotheses are correct, the trends in these modes should be viewed as an integral part of human-induced climate change. The tropical Pacific SST (e.g., NINO3 index measured through the TOGA/TAO array) and pycnocline depth should continue to be used as a metric to evaluate model performance and to diagnose and monitor decadal and longer-term changes in ENSO statistics, which have the potential to be modulated by global climate change.

In the context of this report the month-to-month and year-to-year variations in these natural modes of variability provide an opportunity for verifying model parameterizations of the processes that govern the feedbacks discussed in previous chapters. For example, a faithful simulation of the year-to-year changes in tropical mean temperature, humidity, cloudiness, and rainfall that occur in association with the ENSO cycle requires a realistic treatment of many of the same physical processes that determine the sensitivity of these parameters to global warming. However, unlike forecasts of greenhouse warming, it can be verified on a year-by-year basis. In a similar manner, observed year-to-year changes in stratospheric ozone, sea ice, and snow cover that occur in association with natural fluctuations in the annular modes can be used to diagnose the treatment of processes relevant to ice-albedo feedbacks in climate models.

The observational requirements for defining the evolution of the principal modes of variability of the coupled atmosphere-ocean system are defined in the planning documents for the World Climate Research Program (WCRP) on climate variability and predictability (CLIVAR), as described in NRC (2001d). Studies such as the Pacific Basin Extended Climate Study (Davis et al., 2000) could help test hypotheses concerning the nonstationary behavior of natural modes.

On the national level and in some cases even on the agency level, program planning for climate and global change and that for diagnosing and predicting natural climate variability on seasonal to decadal time scales has been carried out largely by mutually exclusive communities of scientists with relatively little coordination between them. Clearly, there is an opportunity for synergy between the research program on climate sensitivity and feedbacks outlined in this report and the research on climate prediction described in the CLIVAR planning documents.

9

RECOMMENDATIONS

Over the past decade we have learned much about the complex natural processes that influence climate variability and change, and our ability to model climate has increased significantly. We have gained a better appreciation for the important connections between physical, biological, and human dimensions of the climate system. We have also begun to better identify those parts of the climate system that are particularly important and not well understood, and that therefore limit our ability to project the future evolution of Earth's climate. A critical area where understanding is needed is the role of feedbacks in the climate system and their role in determining climate sensitivity.

This Panel believes that refining our understanding of the key climate feedback processes and improving their treatment in models used to project future climate scenarios is an effective way forward in the quest to better understand how climate may evolve in response to natural and human-induced forcings. An appropriate strategy for accomplishing this is to make more rigorous comparisons of models with data and to focus particularly on observational tests of how well models simulate key feedback processes.

This report highlights broad guidance on the key avenues of research that need to be pursued to better understand climate feedbacks and is intended to call attention to those areas where additional focus might be productive in the near term. The key finding of this report is that an enhanced research effort is needed to better observe, understand, and model key climate feedback processes. Research on climate feedback processes should be designed to

- Integrate observational and modeling efforts toward understanding and modeling of climate feedback processes;
- Integrate the subdisciplines of climate science for a comprehensive study of the key climate feedback processes; and

- Integrate different time scales of weather and climate variability into studies of climate feedback processes.

KEY OBSERVATIONS NEEDED TO MONITOR AND UNDERSTAND CLIMATE FEEDBACKS

Because climate feedback processes are so important to understanding climate change, it is necessary to monitor the variables that characterize the feedback processes as well as the variables that define the basic climate. In addition to temperature and precipitation, variables such as clouds, water vapor, aerosols, land surface properties, snow cover, sea ice, and radiation budget quantities need to be monitored. Stable long-term measurements of these variables can be used to monitor the feedback processes, to better understand these processes, to identify the contributing causes to observed climate changes, and to improve confidence in climate projections.

> *Recommendation:*
> *An integrated global climate-monitoring system must include observations of key climate feedback processes. Stable, accurate, long-term measurements should be made of the variables that characterize climate feedback processes.*

As climate and greenhouse gases change, certain variables (see below) must be adequately monitored to advance the objectives of climate change feedbacks research and to define the state of the climate system including feedback processes. Although some of these observations are made, there are deficiencies. Some of these observations are made across insufficient lengths of time or across too limited regions, or are not made routinely and globally as required for global climate monitoring. Other measurements are made globally, but lack the quality required for long-term climate monitoring and analysis (see NRC, 1999a, 2000b).

1. Observations with Insufficient Time or Space Resolution

- Ice thickness;
- Temperature and salinity of the upper ocean and other portions of the ocean that affect interannual to decadal climate change;
- Atmospheric trace gas concentrations (e.g., CO_2, O_2-N_2, CH_4, O_3) and ocean chemistry; and
- Soil moisture profiles and snow properties (e.g., depth, moisture equivalent, snow state).

2. Observations That Do Not Meet Quality Standards[1]

- Temperature and humidity (particularly in the upper troposphere and stratosphere), precipitation, and wind;
- Global cloud and aerosol distributions and properties;
- Sea ice margin characteristics;
- Terrestrial vegetation, and snow extent;
- Radiation budget at the top-of-tropopause and at the surface; and
- Ocean color.

The collection and validation of these datasets will require international collaboration and cooperation among U.S. agencies. As recommended in several previous NRC reports, there are advantages to collecting these observations in the context of an integrated global monitoring system (e.g., NRC, 1999a). Such a system is required for other aspects of climate change research and applications not addressed in this report including climate change attribution and detection and providing a broad range of climate and weather services (NRC, 2001e).

Details of these observation needs were presented in Chapters 2 through 8. As explained in Chapter 2, a water vapor observing system is needed that has sufficient accuracy to measure decadal trends in the water vapor distribution and sufficient spatial resolution to aid in understanding the mechanisms by which the water vapor distribution is maintained. The water vapor observing system should be closely linked to a global cloud, aerosol, and precipitation observing system. As was discussed in Chapter 3, detailed datasets for Arctic and Antarctic ice cover and albedo, and more comprehensive sea-ice thickness data are needed that extend over long periods of time to account for interannual variability. Techniques for efficiently measuring sea-ice thickness over the globe need to be developed.

Improved definition of the basic temperature and salinity state of the upper ocean also is needed, as explored in Chapter 4. This will require full implementation of a system with the capabilities of the Argo global array of profiling floats, plus a strategy for monitoring key regions of the ocean that are important for the thermohaline circulation, such as the Labrador, Greenland-Iceland-Norwegian, Weddell, and Ross seas. The need for integrated datasets for soil moisture, skin and soil temperature, vegetation properties and cover, and snow water equivalent are examined in Chapter 5.

A new suite of in situ and remotely sensed observations are needed to provide information on a variety of aerosol characteristics and key

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[1] As defined in NRC (1999a, 2000b).

atmospheric chemical properties that have been unavailable heretofore on a temporally or spatially extensive basis. These characteristics, outlined in Chapter 6, include the chemical composition of aerosol particles, optical extinction, and scattering under a wide range of conditions. Chapter 7 notes that a highly diverse set of observations is required to more tightly constrain understanding of Earth's biogeochemical feedbacks. These observations include O_2-N_2 ratio, ocean carbon in a variety of forms, ocean color, and atmospheric CO_2 and CH_4 concentration.

EVALUATING PROGRESS IN UNDERSTANDING CLIMATE FEEDBACKS

The simulation of individual feedback processes must be tested against appropriate observations in order to measure our understanding, reveal the reasons why climate sensitivity varies from model to model, and know which models are most likely to be correct. To do this requires a well-designed set of observed diagnostic tests, or metrics, that will measure our understanding and provide standards against which models can be tested. A sufficiently discriminating set of observational tests would lead to improvements in individual models and better methods for objectively rating the performance of climate models.

Recommendation:
Both global and regional metrics that focus on feedback processes responsible for climate sensitivity should be used to more rigorously test understanding of feedback processes and their simulation in climate models.

An expanded set of data comparisons, or climate model performance metrics, should be developed that focus on each of the key climate feedback processes and include geographic and seasonal variations. In this context metrics are robust statistics that can be derived from observations and capture the essence of some fundamental aspect of a phenomenon or process. A first step toward developing metrics to evaluate feedback processes would be for the relevant agencies to organize a workshop or series of workshops to define observational metrics. These workshops would include scientists engaged in observation, diagnosis, and modeling of climate and climate processing.

Effective metrics must be based on a basic description and at least a rudimentary understanding of the phenomenon or process in question. They must be tailored to the variety of time and space scales on which the relevant climate change feedbacks operate. They must be based on measurements that are of good quality and can define the process or phenomenon well. Metrics should evolve as our understanding and observations improve.

A good set of diagnostic tests, or metrics, will do much more than assess the state of a system; it will also capture the co-variation or coupling between the system's components. If effectively employed, metrics can be an essential tool to help organize and stratify diagnostic analyses, as well as to relate model simulations to the fundamental aspects of observed phenomena. They can also be a useful tool to monitor the evolution of the climate system and thus make important contributions to the field of climate change detection and attribution. Utilization of observational metrics as proposed in this report would increase the observational constraints on feedback processes and could help to improve confidence in regional climate projections. A broadly accepted suite of climate feedbacks metrics could also provide a partial solution to the "need for uniform criteria with which to judge climate models," which has been identified as a key issue in a previous NRC report (NRC, 2001c).

Examples of Metrics

Because the magnitude of the changes in feedback processes may not yet have been sufficiently large to evaluate our understanding of the feedbacks as they relate to long-term climate change, it is not possible to fully evaluate an understanding of climate feedback processes by observing long-term trends in global climate. An alternative strategy is to use observations of shorter-term variability to test understanding and simulation of climate feedback processes. Strongly forced variations such as annual, diurnal, and ENSO cycles seem to provide valuable tests for understanding the processes underlying climate change feedbacks.

Although there are benefits to using short-term variability as a diagnostic tool for improving understanding and modeling of climate feedback processes, it is recognized that success in simulating the role of climate feedback processes in short-term climate variations does not necessarily translate to success in simulating global warming. Nevertheless, short-term climate variability provides a promising avenue for quantitatively evaluating the feedback processes of a model used for the study of global warming. In other words, a model may not be regarded as reliable for climate change projections simply because it realistically simulates feedbacks on short time scales. But if a climate model can accurately simulate climate feedback processes on interannual, annual, and shorter time scales, a much stronger argument can be made that it should be reliable for climate change projections.

An example of a large-scale regional metric is the response of atmospheric temperature, water vapor, clouds, radiation fluxes, and atmospheric circulation to sea surface temperature anomalies associated with warm events in the tropical Pacific (e.g., Hartmann and Michelsen, 1993, Ramanathan and Collins, 1991). This approach can be expanded to examine the covariability of sea surface temperature, tropical convection, upper tropospheric water vapor, the vertical profile of atmospheric temperature, and other observations over a variety of time scales, including the seasonal time scale. These covariance metrics should then be applied to model simulations to pinpoint those aspects of the models that appear to accurately represent nature and those that require further work.

On the continents the global warming response of precipitation, clouds, and soil moisture is important. A metric that might enable improvement of feedback processes over land would be the simulation of the observed diurnal variations of temperature, clouds, and precipitation, and the slow evolution of the diurnal cycle on the seasonal timescale as, for example, soil moisture decreases during the summer months. The snow and ice feedback could be quantified by linking the regional climate sensitivity and the amplitude of the seasonal cycle to the snow cover and surface energy balance for latitude-longitude blocks of the North American and Eurasian continents.

Many other possible metrics for testing the simulation of climate system feedbacks can be envisioned. Individual disciplinary chapters in this report give additional examples of metrics that might be used to diagnose specific aspects of climate system feedbacks. The set of metrics will likely evolve with time as understanding and simulation of the climate system evolves and improves.

Climate Modeling and Analysis for Climate Feedbacks Research

A practical goal of climate feedbacks research is to provide information necessary to support more reliable projections of future climates. To test understanding and modeling of climate feedback processes using a set of climate feedback metrics requires a substantial infrastructure and a proportionate intellectual effort. To undertake a rigorous program of testing the simulation of climate feedback processes in our most capable climate models requires that the observations and the expertise in applying them be brought together with the modeling capability. Previous NRC reports have stated the need for capable and effective climate modeling facilities (NRC 1998c, 2001c), and have recommended the development of centralized operations for climate predictions and ozone assessments (NRC, 2001c). To advance understanding of climate change feedbacks and their role in climate sensitivity it is essential that U.S. climate modeling facilities also have the capability and mandate to test climate feedback processes and their interactions using the most discriminating observational constraints. Within the context of climate feedback processes this will also address the need for uniform criteria with which to judge climate models (NRC, 2001c).

The Panel on Improving the Effectiveness of U.S. Climate Modeling has previously noted "the need for strong interaction between observations of the climate system, research into fundamental climate processes, and integrative climate modeling" (NRC, 2001c). That same panel recommended enhanced resources for centralized operational activities addressed to short-term climate predictions, to the study of predictability of climate on decadal and century time scales, and to assessments of ozone depletion and climate change (NRC, 2001c).

A research program that uses observable metrics to test our understanding and simulation of climate change feedbacks should be applied most assiduously to the models that are most capable of both simulating the complex interactions of the various feedback processes and making climate change projections for planning purposes. Applying the most stringent observational constraints and tests to the most capable integrated models will benefit climate feedbacks research and increase our confidence in the climate projections made with these models. For this reason it is important that the research and operational facilities operating the most capable climate models have access to the data and expertise necessary to employ the most discriminating metrics of the feedback processes.

> *Recommendation:*
> *Climate modeling facilities in the United States must be given the capability and mandate to test understanding and simulation of climate feedback processes and their interactions using the best observational constraints on climate feedback processes. Periodic assessment of the progress being made by major climate models should be conducted to evaluate the ability of these models to simulate the processes underlying key climate system feedbacks.*

Testing and development of climate models can make more effective use of existing datasets, and should rapidly incorporate new datasets as they become available. It is important that these efforts focus more directly on issues related to the specific testing and quantification of feedback mechanisms in climate models.

The Atmospheric Model Intercomparison Project (AMIP) and the Coupled Model Intercomparison Project (CMIP) have been very useful for evaluating the performance of GCMs in simulating the geographical distribution of climate and its seasonal variation (e.g, Covey et al., in press; Gates et al., 1998). These analyses indicate relatively good matches between some aspects of the observed climate and the climate produced by state-of-the-art GCMs. It is highly desirable to develop a specific methodology for the improvement and quantitative assessment of modeled feedback processes and their effect on climate sensitivity. The approach recommended here is a more specific focus on comparing observed measures of climate feedback processes with the same measures produced by climate models. Representations of critical climate processes in climate models are becoming more realistic and must be rigorously tested against all available observations. These efforts should remain focused on the objective of producing more robust model representations of nature, and be prioritized according to their impact on projections of future climates.

One approach for facilitating model improvements of key processes is the Climate Process Team (CPT) concept, currently being developed by the U.S. CLIVAR program. It has the potential to foster more comprehensive investigations of climate change feedbacks. In this approach, teams of scientists, including observationalists, process modelers, and global climate modelers, are to undertake relatively comprehensive and integrated projects focused on specific climate feedback processes and their treatment in climate models. CPTs have the potential to make significant progress toward reducing and better characterizing uncertainty associated with climate change feedbacks, provided that they can develop and maintain a sharp focus on the objective of improving model representations of the key processes.

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APPENDIX A

CLIMATE CHANGE FEEDBACKS WORKSHOP
BOULDER, COLORADO
AUGUST 13-16, 2001

AGENDA

Monday, August 13

8:30 A.M. **Introductions, discussion of the motivation for the workshop,** its objectives, the ensuing study process, etc.
Dennis Hartmann

9:00 A.M. **Keynote talk**: "Perspectives on climate change science and where we need to be going"
Jerry Mahlman

10:00 A.M. **Broad policy and scientific issues** associated with characterizing and reducing feedback uncertainty.
Session Chair: Dan Sarewitz

- Issues viewed from the top
    - Policy implications of characterizing and reducing feedback uncertainty—Neal Lane
- Science
    - Implications of multiple climate change diagnostics for uncertainties in climate system properties—Peter Stone
    - Reducing feedback uncertainty in climate models—Syukuro Manabe

  - A framework for assessing the nonlinear interactions between multiple climate feedbacks—Bill Rossow
- Policy
  - Prioritizing the policy relevance of climate change feedback research—Robert Lempert
  - Climate change feedbacks within a broad policy context—Roger Pielke, Jr.

2:00 P.M. **Lapse rate, water vapor, and cloud feedbacks**
Session Chair: Dian Seidel
Session Rapporteur: David Randall

- Water vapor and lapse rate feedbacks—Brian Soden
- Interactions between global warming and stratospheric ozone depletion—Drew Shindell
- Cloud feedbacks—Graeme Stephens
- Indirect cloud feedbacks—Graham Feingold
- Panel discussion—Stephens, Rossow, Soden, Feingold, Shindell, Sherwood

Tuesday, August 14

8:30 A.M. **Ocean circulation and biogeochemical feedbacks on climate change**
Session Chair: Lynne Talley
Session Rapporteur: Andrew Weaver

- Thermohaline circulation changes—Peter Gent
- Other ocean circulation feedbacks—Jim McWilliams
- Sea ice feedback—Doug Martinson
- Marine biogeochemistry—Tony Michaels
- Panel discussion—Gent, Talley, Semtner, Martinson, McWilliams, Flato, Gruber, Michaels, Lynch, Najjar, and Levitus

1:45 P.M. **Influence of natural modes of variability**
Session Chair: Gene Rasmusson
Session Rapporteur: Tony Busalacchi

- ENSO and other Pacific modes—Kevin Trenberth
- Annular mode—Mike Wallace
- Atlantic modes of variability—Jim Hurrell
- Panel discussion—Hurrell, Wallace, Shindell, Trenberth, Clement, Lukas, Meehl

Wednesday, August 15

8:30 A.M. **Terrestrial feedbacks**
Session Chair: Eric Wood
Session Rapporteur: Gordon Bonan

- Overview—Bob Dickinson
- Soil moisture feedback—Alan Betts
- Snow cover feedback—Dennis Lettenmaier
- Carbon cycle feedbacks—Richard Houghton
- Vegetation feedbacks—Roger Pielke, Sr.
- Panel discussion—Dickinson, Wofsy, Lettenmaier, Betts, Pielke Sr.

12:30 P.M. **Synthesis:** "Probabilistic Approaches to Determine the Relative and Absolute Importance of Different Sources of Uncertainty for Projections of Future Global-mean Temperature Change"
Tom Wigley

Presentations by Rapporteurs—summarize key issues in a forward-looking manner for each of the workshop's earlier sessions. The emphasis will be on what we need to do differently or better, rather than on simply restating the current state of the science.

Thursday, August 16

8:30 A.M. **Synthesis**—continued
Workshop leaders summarize the key points from the previous day's discussion and then open up the meeting for a discussion of the "next steps" in which science needs to proceed to make progress on characterizing and reducing

climate change feedback uncertainties.

10:45 A.M. **Closed Session**
Closed session deliberations of the NRC Panel.

Agenda Postscript:

Because atmospheric chemistry was given only minor attention at this workshop, the Panel subsequently enlisted Michael Prather as a consultant to provide additional input.

MEETING PARTICIPANTS

Panel on Climate Change Feedbacks

Dennis Hartmann *(Chair)*	University of Washington
Alan Betts	Atmospheric Research
Gordon Bonan	National Center for Atmospheric Research
Lee Branscome	Environment Dynamics Research, Inc.
Tony Busalacchi	University of Maryland
Amanda Lynch	University of Colorado
Syukuro Manabe	Princeton University
Douglas Martinson	Lamont-Doherty Earth Observatory, Columbia University
Raymond Najjar	Pennsylvania State University
Eugene Rasmusson	University of Maryland
A. R. Ravishankara	National Oceanic and Atmospheric Administration Aeronomy Laboratory
Daniel Sarewitz	Columbia University
Dian Seidel	National Oceanic and Atmospheric Administration Air Resources Laboratory
Graeme Stephens	Colorado State University
Lynne Talley	Scripps Institution of Oceanography, University of California at San Diego
John M. Wallace	University of Washington
Andrew Weaver	University of Victoria
Steven Wofsy	Harvard University
Eric Wood	Princeton University

Participants

Anjuli Bamzai	National Science Foundation
Roger Barry	University of Colorado
Maurice Blackmon	National Center for Atmospheric Research
David Carson	World Climate Research Programme
John Christy	University of Alabama-Huntsville
Amy Clement	University of Miami
Robert Dickinson	Georgia Institute of Technology
Randy Dole	National Oceanic and Atmospheric Administration

Mark Eakin	National Oceanic and Atmospheric Administration
Graham Feingold	National Oceanic and Atmospheric Administration
Peter Gent	National Center for Atmospheric Research
Chuck Hakkarinen	Electric Power Research Institute
Andrew Heidinger	National Oceanic and Atmospheric Administration
Marty Hoerling	National Oceanic and Atmospheric Administration
Richard Houghton	Woods Hole Research Center
Jim Hurrell	National Center for Atmospheric Research
Neal Lane	Rice University
David Legler	U.S. Climate Variability and Predictability Program Office
Robert Lempert	RAND Corporation
Sydney Levitus	National Oceanic and Atmospheric Administration
Johnny Linn	University of Colorado
Roger Lukas	University of Hawaii
Mike MacCracken	U.S. Global Change Research Program
Jerry Mahlman	University Corporation for Atmospheric Research
Jerry Meehl	National Center for Atmospheric Research
Tony Michaels	University of Southern California
Chris Miller	National Oceanic and Atmospheric Administration
Jeff Miroche	University of Colorado
Mitch Moncrieff	National Center for Atmospheric Research
George Ohring	National Oceanic and Atmospheric Administration
Roger Pielke, Jr.	National Center for Atmospheric Research
Roger Pielke, Sr.	Colorado State University
Robert Pincus	National Oceanic and Atmospheric Administration
David Randall	Colorado State University
Aaron Rivers	University of Colorado
William Rossow	National Aeronautics and Space Administration Goddard Institute for Space Studies
Peter Schultz	National Research Council
Bert Semtner	Naval Research Laboratory

Steve Sherwood	Yale University
Drew Shindell	National Aeronautics and Space Administration Goddard Institute for Space Studies
Andrew Slater	University of Colorado
Tony Socci	U.S. Environmental Protection Agency
Brian Soden	National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory
Jud Stailey	Office of the Federal Coordinator for Meteorology
Peter Stone	Massachusetts Institute of Technology
Yogesh Sud	National Aeronautics and Space Administration Headquarters
Kevin Trenberth	National Center for Atmospheric Research
Rodney Viereck	National Oceanic and Atmospheric Administration
Warren Washington	National Center for Atmospheric Research
Peter Webster	University of Colorado
Tom Wigley	National Center for Atmospheric Research
Sam Williamson	Office of the Federal Coordinator for Meteorology

APPENDIX B

BIOGRAPHICAL SKETCHES OF PANEL MEMBERS

Dennis L. Hartmann (chair), is chair of the Department of Atmospheric Sciences at the University of Washington, Seattle. He holds a Ph.D. in geophysical fluid dynamics from Princeton University. His early work used newly acquired satellite data to investigate the dynamical climatology of the Southern Hemisphere stratosphere. Dr. Hartmann has published more than 100 papers on a wide variety of topics, including radiative-chemical dynamical interactions in the stratosphere, Earth's radiation balance, the role of clouds in climate sensitivity, large-scale dynamics, and numerical modeling. His NRC experience includes the Panel on the Tropical Ocean Global Atmosphere Program, the Committee on Earth Studies, and the Committee on Solar-Terrestrial Research. He is a fellow of the American Association for the Advancement of Science, the American Meterological Society, and the American Geophysical Union.

Alan K. Betts holds a Ph.D. in meteorology from Imperial College (U.K.). In the 1980s Dr. Betts and Martin Miller developed a parameterization of convection for use in global atmospheric models. In contrast to increasingly complex parameterizations involving detailed models of cloud processes, the Betts-Miller scheme takes an "external" view of convection and adjusts the large-scale convective environment toward thermodynamic profiles. Dr. Betts is the chief scientist of Atmospheric Research (Pittsford, Vermont) and is a visiting scientist at the European Centre for Medium Range Weather Forecasts and at NASA's Goddard Space Flight Center. Dr. Betts has served on the NRC Advisory Panel for the International Satellite Cloud Climatology Project and has been a reviewer of the NRC reports *Emerging Global Water and Energy Initiatives: An Integrated Perspective* (1999) and *Improving the Effectiveness of U.S. Climate Modeling* (2001).

Gordon B. Bonan is a senior scientist in the National Center for Atmospheric Research's (NCAR) Climate and Global Dynamics Division and is an associate professor adjoint in the University of Colorado's Program in Atmospheric and Oceanic Sciences. Since 1989 he has worked at NCAR studying the ecological and hydrological processes by which natural and human-mediated changes in land cover affect climate. He serves as an editor for the *Journal of Climate* and holds a Ph.D. in environmental sciences from the University of Virginia.

Lee E. Branscome received his Ph.D. in meteorology from the Massachusetts Institute of Technology in 1981. He spent several years on the faculty of the University of Miami teaching courses in geophysical fluid dynamics and performing climate dynamics research sponsored by the National Science Foundation and National Aeronautics and Space Administration. As president of Environmental Dynamics Research, Inc., Dr. Branscome has performed weather and climate studies for businesses, law firms, and government agencies since 1988. He has served as president of the National Council of Industrial Meteorologists and chairman of the Board of Certified Consulting Meteorologists of the American Meteorological Society. His current research activities are primarily focused on helping businesses understand and manage their weather and climate risk. Dr. Branscome is a member of the National Council of Industrial Meteorologists, the American Meteorological Society, and the American Geophysical Union.

Antonio J. Busalacchi, Jr., is the Director of the Earth System Science Interdisciplinary Center and professor of meteorology at the University of Maryland, College Park. His research interests include climate variablity, the development and application of numerical models combined with in situ and space-based ocean observations to study the tropical ocean response to surface fluxes of momentum and heat, as well as tropical ocean circulation and its role in the coupled climate system. Dr. Busalacchi has NRC experience as a member of the Panel on the Tropical Ocean Global Atmosphere Program, the Panel on Ocean Atmosphere Observations Supporting Short-Term Climate Predictions, Committee on Earth Studies, and is presently chair of the Climate Research Committee. He holds a Ph.D. in oceanography from Florida State University.

Amanda H. Lynch is an assistant professor in the Program in Atmospheric and Oceanic Science and a fellow of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. Dr.

Lynch received her Ph.D. in meteorology from the University of Melbourne in 1993. Her research interests include climate system modeling, process modeling, and fieldwork on high-latitude climate. Current projects include studies on the interactions atmospheric circulation and sea-ice cover, the effects of vegetation and snow distribution on climate, both past and present, and the hydrological cycle. Dr. Lynch is a member of the American Meteorological Society and the American Geophysical Union and serves on the National Science Foundation's Office of Polar Programs Advisory Committee.

Syukuro Manabe is a visiting research collaborator of the Program in Atmospheric and Oceanic Sciences at Princeton University. During most of his career he was the leader of the Climate Dynamics Group at Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration. His group developed a hierarchy of climate models of various complexities, ranging from one-dimensional, radiative-convective models of the atmosphere to three-dimensional models of the coupled ocean-atmosphere-land surface system. Using these models they explored the physical mechanisms that are responsible for the forced and unforced climatic changes of the past, present, and future, in particular, global warming. Dr. Manabe's NRC service includes the Panel on Climate Variability on Decade-to-Century Time Scales, Board on Atmospheric Sciences and Climate, and Commission on Geosciences, Environment, and Resources. He is a honorary member of the American Meteorological Society and the Japan Meteorological Society, and a fellow of the American Geophysical Union and American Association for the Advancement of Science. He is a member of the National Academy of Sciences.

Douglas G. Martinson is a Doherty Senior Research Scientist at Lamont-Doherty Earth Observatory and an adjunct professor in the Department of Earth and Environmental Sciences at Columbia University. Dr. Martinson's primary research foci are the oceans and their role in climate. In particular, he studies the interactions of air, sea, and ice in high-latitude oceans; how these interactions govern the distribution of sea ice; and how changes in sea-ice cover can affect the world's deep-ocean circulation and global climate. Dr. Martinson's research includes both modeling and observational studies in polar regions, typically during winter months, from ships or camps set up on the sea ice. He is also interested in the relationship between oceans and climate over longer time scales, typically focusing on the role of high-latitude oceans in the onset and termination of the ice ages. Dr. Martinson has previous NRC experience as chairman of the Panel on Climate

Variability on Decade-to-Century Time Scales and as a member of the Climate Research Committee.

Raymond Najjar is an associate professor at the Pennsylvania State University. He is an oceanographer with broad research interests. He has studied the global-scale cycles of carbon, oxygen, and nutrients in the ocean, using both observations and models. He is also interested in photochemically produced gases in the sea, particularly carbon monoxide, and is engaged in fieldwork and modeling of this gas. Dr. Najjar also makes simple models of estuaries and their watersheds and uses them to quantify the potential impact of climate change on these systems. He has used numerical models to study past changes in ocean circulation and dissolved oxygen. Dr. Najjar served on the steering committee of the Joint Global Ocean Flux Study and has written numerous articles in both U.S. and foreign scientific publications.

Eugene M. Rasmusson is a Research Professor Emeritus at the University of Maryland, College Park. His research expertise lies broadly in seasonal-to-interannual climate variability, with emphasis on the global hydrologic cycle, tropical variability, and the nature and predictability of the El Niño-Southern Oscillation phenomenon. Dr. Rasmusson's NRC experience is wide-ranging and includes membership on the Board on Atmospheric Sciences and Climate, the Global Ocean-Atmosphere-Land System Panel, the Panel on Model-Assimilated Datasets for Atmospheric and Oceanic Research, the Committee on USGS Water Resources Research, and the Advisory Panel for the Tropical Ocean/Global Atmosphere (TOGA) Program. He is a member of the National Academy of Engineering.

A. R. Ravishankara is a senior scientist at the National Oceanic and Atmospheric Administration's Aeronomy Laboratory and a professor adjoint at the University of Colorado, Boulder. He has made fundamental contributions to understanding and quantifying important processes critical to the chemistry of the atmosphere. He has used highly innovative techniques to advance the knowledge of ozone depletion, climate change, and atmospheric pollution, and has thereby played a leadership role in shaping understanding of global chemical changes. Dr. Ravishankara's major research interest is to understand what happens to molecules released into the atmosphere and how these molecules affect the atmosphere. He identifies and quantifies middle- and lower-atmospheric chemical processes through laboratory studies. His group studies the thermal gas phase reactions, photochemical processes, and heterogeneous and multiphase reactions of various chemical species known or expected to be present in the atmosphere.

Dian J. Seidel leads the climate variability and trends group at the NOAA Air Resources Laboratory in Silver Spring, Maryland. Her recent research focuses on observational studies of atmospheric temperature and water vapor changes, climate extremes, and meteorological data quality. She is a member of the American Meteorological Society and the American Geophysical Union and a recipient of the Professor Dr. Vilho Vaisala Award and the Norbert Gerbier-Mumm Award, both from the World Meteorological Organization, as well as the NOAA Administrator's Award. Dr. Seidel is a fellow of the American Meteorological Society and a former member of the NRC Climate Research Committee.

Graeme L. Stephens is a professor in the Department of Atmospheric Science at Colorado State University. He received his Ph.D. in 1977 from the University of Melbourne. Dr. Stephens's research activities focus on atmospheric radiation and on the application of remote sensing in climate research, with particular emphasis on understanding the role of hydrological processes in climate change. His work has focused on understanding cloud radiation interactions as relevant to Earth's climate using both theory and numerical modeling as well as analysis of cloud properties from measurements made by satellites and aircraft. Dr. Stephens is currently the principle investigator of NASA's Cloudsat Mission. Dr. Stephens's professional activities currently include editor of a number of leading atmospheric science journals, past chairman of the WCRP GEWEX radiation panel and the American Meteorological Society Atmospheric Radiation panel. He is a fellow of both the American Geophysical Union and the American Meteorological Society. Dr. Stephens is a former member of the NRC Board on Atmospheric Sciences and Climate, the Climate Research Committee, and the Committee on Earth Sciences.

Lynne D. Talley is a professor of oceanography at the Scripps Institution of Oceanography at the University of California San Diego. Dr. Talley's expertise and research interests lie in general ocean circulation, water mass formation, and ocean heat transport. She has an extensive NRC background and currently serves on the Climate Research Committee and was a member of the recent Abrupt Climate Change Committee. She has also served on the Global-Ocean-Atmosphere-Land System Panel and Panel to Review the Jet Propulsion Laboratory Distributed Active Archive Center. Dr. Talley is a member of the American Geophysical Union, American Meteorological

Society, and Oceanography Society, and is a trustee of the University Corporation for Atmospheric Research. She was a National Science Foundation Presidential Young Investigator in 1987 and received the Rosenstiel Award in 2001. She is a fellow of the American Academy of Arts and Sciences.

John M. Wallace is a professor of atmospheric sciences at the University of Washington, Seattle. His research specialties include the study of general climate circulation and tropical meteorology. Dr. Wallace has applied innovative dynamical and statistical techniques to pioneer the characterization of atmospheric circulation systems in time and space and their links to ocean and land surface conditions. He discovered the pattern that relates tropical El Niño events to North American climate anomalies. He has contributed to the identification and understanding of a number of atmospheric phenomena, including the vertically propagating planetary waves that drive the quasi-biennial oscillation in zonal winds in the equatorial stratosphere, the four- to five-day easterly waves that modulate daily rainfall over the tropical oceans, and the dominant spatial patterns in month-to-month and year-to-year climate variability. He is a member of the American Meteorological Society, the American Geophysical Union, and the National Academy of Sciences.

Andrew J. Weaver is a professor and Canada Research Chair in Climate Modelling and Analysis in the School of Earth and Ocean Sciences, University of Victoria. He was involved as a lead author in the U.N. Intergovernmental Panel on Climate Change second and third scientific assessments of climate change and currently serves on the U.N. World Climate Research Programme Working Group on Coupled Modelling. He is an editor of the *Journal of Climate* and a fellow of the Royal Society of Canada. His research expertise concerns the role of the ocean in past, present, and future climate.

Steven C. Wofsy is the Abbott Lawrence Rotch Professor of Atmospheric and Environmental Sciences in the Department of Earth and Planetary Sciences at Harvard University. Dr. Wofsy holds a Ph.D. in chemistry from Harvard University. He studies a variety of atmospheric gases using instruments aboard aircraft and also on the ground at long-term measurement sites. His research interests include undertaking theoretical and modeling studies to understand depletion of stratospheric ozone in polar regions, to assess future impacts of pollutants injected into the stratosphere, and to examine ecological and historical factors affecting atmospheric concentrations of CO_2. In 2001 Dr. Wofsy received the Distinguished Public Service Medal from the National Aeronautics and Space Administration. He is a fellow of the American Geophysical Union and the American Association for the Advancement of Science.

Eric F. Wood is a professor of civil and environmental engineering at Princeton University, where he has taught since 1976. He received his Sc.D. in civil engineering from the Massachusetts Institute of Technology. From 1974 to 1976 he was a resident scholar at the Institute of Applied Systems Analysis in Austria. His research areas include hydroclimatology with an emphasis on land-atmospheric interaction, hydrological remote sensing, and hydrologic impact of climate change. He is also a member of the NRC Committee on Hydrological Sciences, where he serves as chair. He is a former member of the NRC Board on Atmospheric Sciences and Climate and the Water Science and Technology Board. Dr. Wood is a fellow of the American Geophysical Union and of the American Meteorological Society. He has received the Robert E. Horton Award and the Rheinstein Award and has conducted a Robert E. Horton Memorial Lectureship.

APPENDIX C

ACRONYMS AND ABBREVIATIONS

AIRS	Advanced infrared sounder
AMIP	Atmospheric Model Intercomparison Project
AO	Atlantic oscillation
ARM	Atmospheric Radiation Measurement Project (DOE)
AVHRR	Advanced very high resolution radiometer
BOREAS	Boreal Ecosystem-Atmosphere Study
LBA	Large-Scale Biosphere-Atmosphere Experiment in Amazonia
CART	Cloud and Radiation Testbed
CCN	Cloud condensation nuclei
CERES	Clouds and the Earth's radiant energy system
CFCs	Chlorofluorocarbons
CLIVAR	Climate variability and predictability (WCRP)
CMIP	Coupled Model Intercomparison Project
CPT	Climate Process Team
CRM	Cloud-resolving model
DMS	Dimethylsulphide
DMSP	Dimethylsulfoniopropionate
DOE	Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
ERBE	Earth Radiation Budget Experiment
FIFE	First ISLSCP field experiment
GCM	General Circulation Model
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GIN	Greenland, Iceland, and Norway
GISS	Goddard Institute for Space Studies
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GPCP	Global Precipitation Climatology Project

ISCCP	International Satellite Cloud Climatology Project
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
IN	Ice condensation nuclei
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LDAS	Land Data Assimilation System
LTER	Long Term Ecological Research program
MISR	Multiangle Imaging SpectroRadiometer
MOC	Meridional overturning circulation
MODIS	Moderate resolution imaging spectroradiometer
MSA	Methanesulphonate
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NVaP	NASA Water Vapor Project
NWP	Numerical weather prediction
P-E	Precipitation minus evaporation
PIRATA	Pilot Research Moored Array in the Tropical Atlantic
SHEBA	Surface Heat Budget of the Arctic Ocean
SOLAS	Surface Ocean Lower Atmosphere Study
SST	Sea surface temperature
TOGA	Tropical Ocean Global Atmosphere
TAO	Tropical Atmosphere Ocean array
TAR	IPCC Third Assessment Report
TOA	Top of the atmosphere
ULS	Upward-looking sonar
USCCSP	U.S. Climate Change Science Plan
USGCRP	U.S. Global Change Research Program
UV	Ultraviolet
WCRP	World Climate Research Programme
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermograph