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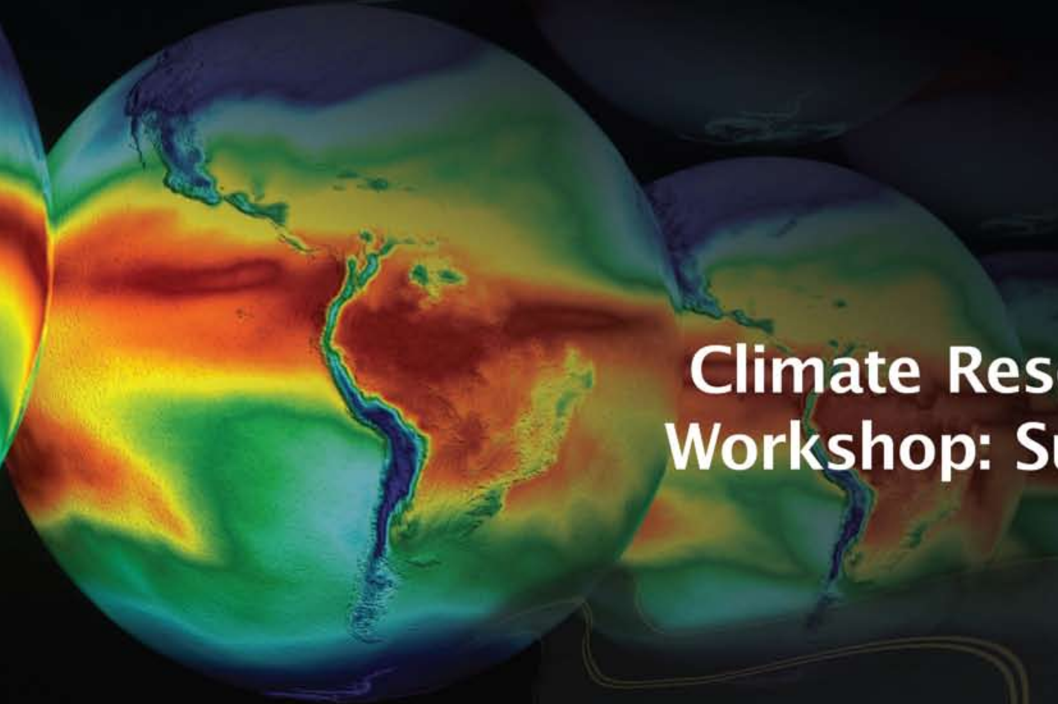
Climate Research Roadmap Workshop: Summary Report

May 13–14, 2010



U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Biological and Environmental Research

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This workshop report is available at www.sc.doe.gov/ober/BER_workshops.html.

Contents

1. Introduction

The U.S. Department of Energy (DOE) Office of Science works at the interface of climate and energy with the recognition that energy production and use have led to an increase in anthropogenic greenhouse gas emissions and changes in Earth's climate. DOE has a long history of characterizing the interplay of climate and energy. For example, it developed the first general circulation models (GCMs), the forerunners of today's climate models, to understand and predict the atmospheric movement of radioactive particles from nuclear weapons testing. It also supported critical large-scale manipulative ecological studies to understand the role of terrestrial ecosystems in climate change. DOE's energy mission led to the first federally funded program to study the relationship between atmospheric carbon dioxide and climate change. Subsequent collaborative efforts produced the first terrestrial carbon cycle models. DOE developed and deployed the Atmospheric Radiation Measurement program (ARM) to understand the relationships between solar radiation and clouds, still one of the greatest uncertainties in climate science. DOE is responsible for the Program for Climate Model Development and Intercomparison (PCMDI), which creates improved methods and tools for diagnosing and intercomparing GCMs that simulate the global climate. DOE also develops models of individual climate system components, including the leading ones for oceans (Parallel Ocean Program; POP) and sea ice (Community Ice Code; CICE) and, in cooperation with the National Science Foundation, the Community Land Model (CLM). These DOE-supported activities have contributed to international efforts to understand and predict Earth's changing climate.

1.1 BER's Major Research Areas for Climate

Within DOE's Office of Science, the Office of Biological and Environmental Research (BER) is responsible for an integrated program of basic science that is developing a predictive, systems-level understanding of the coupled Earth system. Today, DOE's basic climate science programs are providing unique, world-leading capabilities in climate modeling and cloud, aerosol, and ecosystem/carbon cycle research. These programs also are improving our understanding of the effects of greenhouse gas emissions on Earth's climate and the biosphere and building foundational science to support effective energy and environmental decision making. BER carries out this scientific mission by tightly coupling theory, observations, experiments, and models and simulations with scientific emphases in three major areas: (1) Atmospheric System Research, (2) Environmental System Science, and (3) Climate and Earth System Modeling.

Atmospheric System Research (ASR). This research seeks to better understand two major uncertainties in climate change projections: the role of clouds and the effects of aerosol emissions on Earth's radiation balance. This program is coupled to and benefits from observational data generated by the Atmospheric Radiation Measurement (ARM) Climate Research Facility. A multiplatform national scientific user facility, the ARM Climate Research Facility has instruments at fixed and varying locations around the globe for obtaining continuous, long-term field measurements of climate data. The facility promotes the advancement of atmospheric-process understanding and climate models through precise observations of atmospheric phenomena and is tied closely to ASR research activities.

Environmental System Science. This research seeks to understand the terrestrial fate, transport, and impacts of energy-related environmental contaminants, including carbon dioxide. Within this broad scope, the Terrestrial Ecosystem Science activity develops scientific understanding of how climate change affects terrestrial ecosystems and what role they play in global carbon cycling.

Climate and Earth System Modeling. This research seeks to improve our understanding of current and future climate by:

1. Developing, evaluating, and using regional and global models to obtain more accurate projections of future climate at higher resolution.
2. Developing improved representations of specific model components (e.g., atmosphere, ocean, land, sea ice, and ice sheets)—along with better coupling mechanisms—and integrating them into Earth System Models that take advantage of DOE's high-performance computing capabilities.
3. Developing and using Integrated Assessment Models to determine the impacts from and possible mitigation of climate change. This research activity includes exploring the complex interactions of human and natural Earth systems.

BER's climate research communities are coordinated with those of other federal agencies through the U.S. Global Change Research Program (USGCRP) and its subsidiary Interagency Working Groups (IWGs).

1.2 Workshop Approach and Goals

In 2008, the BER climate research program developed a strategic plan, which since has prompted a number of organizational and scientific advances. These include further consolidation of climate research activities within BER; an updated program-specific plan for ASR; and several topical workshops and associated reports, such as *Scientific Grand Challenges: Challenges in Climate Change Science and the Role of Computing at the Extreme Scale; Science Challenges and Future Directions: Climate Change Integrated Assessment Research;* and *Carbon Cycling and Biosequestration: Integrating Biology and Climate Through Systems Science.* In addition, the USGCRP and research programs at its member agencies continue to evolve.

In recognition of the ongoing advances and challenges of climate change research, BER organized a workshop asking the scientific community to identify the current state of climate science. The goal of the workshop was to determine the research challenges important for developing a predictive understanding of global climate. Participants were asked to focus on interdisciplinary research that capitalized on BER's scientific strengths in Atmospheric System Research, Terrestrial Ecosystem Science, and Climate and Earth System Modeling. Approximately 50 scientists representing these three areas were asked to identify desired outcomes for the next 10 years. Goals were identified for the near (1–3 years), mid (4–7 years), and long term (8–10 years). Discussions were focused by discipline (atmospheric, terrestrial, and modeling) and by latitude (high, temperate, and tropical). In addition, opportunities and needs for integration across disciplines and latitudes were identified with a specific focus on crosscutting challenges and outcomes. BER will use this workshop output to update its strategic plan for climate research.

Science leads were identified for each of the three disciplinary areas (atmospheric, terrestrial, and modeling). These leads assembled writing teams who drafted discussion papers for each area. To stimulate thinking prior to the workshop, the three discussion papers were posted on a blog, and all participants were invited to read and comment on descriptions of current situations; inputs and resources; desired outcomes; and near-, mid-, and long-term goals outlined for each science area. On the first day of the workshop, discussions were organized by these three scientific disciplines. In addition, workshop participants charged with identifying crosscutting challenges and opportunities circulated among the three disciplinary breakout groups soliciting input on opportunities and needs for integration. The second day focused on research challenges from a latitudinal perspective (high, temperate, and tropical) to encourage integrative, cross-disciplinary thinking.

Following the workshop, the leads and their writing teams updated the discussion papers and drafted an integration paper. The four discussion papers (atmospheric science, terrestrial science, climate modeling, and integrating science) are included as chapters in this workshop summary report. BER program staff also used workshop presentation materials and detailed staff notes of workshop discussions to develop this report.

2. Workshop Summary

The Department of Energy (DOE) brings a unique and critical blend of research resources, infrastructure, and policy to the U.S. effort to understand and project the impacts of energy production and use on climate change. As one of the leaders of U.S. climate change research, DOE's Office of Biological and Environmental Research (BER) strives to improve the effectiveness of its climate science programs. The BER climate science portfolio includes world-leading capabilities in research and climate modeling that address major knowledge gaps in our understanding of climate change, such as clouds and aerosols and the carbon cycle. BER is the major U.S. supporter of ground-based observations of clouds and their processes, ocean and sea-ice modeling, Integrated Assessment Modeling, and large-scale ecosystem manipulation experiments. BER leverages climate research investments by other federal agencies, such as remote sensing capabilities of the National Aeronautics and Space Administration (NASA) and ship-based ocean programs of the National Oceanic and Atmospheric Administration (NOAA). BER also collaborates with the U.S. Department of Agriculture and the National Science Foundation (NSF) on the development of decadal and regional climate prediction using Earth System Models (ESMs). Other synergies include international programs that provide additional data and observations for developing state-of-the-art climate models.

2.1 Climate Research Recommendations

Workshop participants acknowledged BER's vital contributions to national and international efforts in climate science, particularly in climate modeling, clouds and aerosols, and ecosystem research. In workshop discussions, seven overarching recommendations emerged for the next 10 years of BER climate research.

1. Build upon BER Strengths in Integrated, Model-Inspired Science to Understand Complex Earth Systems

The goal of the BER Climate and Environmental Sciences program is to understand the behavior of coupled Earth systems. The inherent complexity of these systems and our limited ability to observe processes and interactions as they occur have proven to be major challenges to predictive climate simulations at the global scale and over extended time frames. Understanding such complex systems will require a strong component of integrated, multidisciplinary research. The concept of coupling and integration was a recurrent theme during the workshop and is reflected throughout this document. Future integrated studies of Earth system dynamics should be designed to focus on sensitive parts of the system, as suggested by analysis of modeling results. Integrated studies then are designed to take a systems approach to understanding a complex system (e.g., the carbon cycle) and to apply the disciplines and scales necessary to answer the specified questions. Results of such integrated research are well aligned to inform both process and fully coupled models. Spatial scaling from molecular to regional to global then can be reflected in corresponding models, with critical information and process understanding translated from one scale to another. This approach to understanding complex physical, biological, and environmental systems is unique to BER and important to supporting DOE mission needs.

2. Foster Balanced Program of Discovery and Use-Inspired Research

Within BER, there is a need to balance and connect the integrated, research campaign approach described below with discovery research focused on specific processes within the climate system. BER's research is closely connected to DOE mission needs, and being able to address those needs in both the near and long term requires a continuing evaluation to balance the longer-term investments associated with discovery research with the shorter-term investments associated with use-inspired research. Discovery research is a hallmark of DOE's Office of Science and provides the scientific foundations for future advances in understanding. Within BER's climate program, discovery research includes studies on the chemical evolution of atmospheric aerosols, cloud microphysics, the role of microbial processes in soil carbon cycling, ecosystem community succession under changing climate scenarios, and improved numerical techniques for representing complex systems in global models. An area that illustrates BER's use-inspired research is the integrated assessment of climate change—where knowledge gained from discovery science is synthesized, subjected to further basic research, and ultimately expressed in the form of leading Integrated Assessment Models (IAMs) that are used by the scientific community, planners, and decision makers alike. For example, IAMs are used by the science community to drive scenarios, to make climate model assumptions that underpin Intergovernmental Panel on Climate Change studies, to provide insights on energy technology options and implications for greenhouse gas stabilization options, and, increasingly, to help reveal multisectoral impacts and vulnerabilities and decision options at the mitigation-adaptation interface. A careful balance of discovery science and use-inspired research provides important scientific advances to address the needs of the broader climate research community while also advancing the basic sciences underpinning DOE missions.

3. Develop and Support Targeted Scientific Research Campaigns

The concept of scientific research campaigns arose independently in several workshop sessions as one approach that can be applied to a range of scales and scientific challenges. This approach would direct the research community to focus on a few tractable challenges over short periods of time and to structure its research around the delivery of scientific "products." BER has a history of deploying targeted research campaigns to understand and predict large, coupled complex systems and currently applies this approach to specific process science areas (e.g., Intensive Operational Periods for Atmospheric Radiation Measurement (ARM) and Free-Air CO_2 Enrichment experiments). Future research campaigns could be conducted within a particular discipline—involving, for example, the synthesis of existing knowledge regarding carbon flux or efforts to improve the representation of tropical precipitation in global climate models. Research campaigns also could span disciplines, such as improved understanding and model representation of critical Arctic processes. The research campaign approach identifies specific scientific challenges and applies the necessary efforts in data collection, experimentation, and synthesis and modeling to resolve the issue. This approach is well aligned with BER's scientific capabilities and strengths.

4. Understand and Quantify Uncertainty in Climate Projections

Quantifying the uncertainty of model results not only will provide critical information needed to inform science-based policy decisions, but also will support the integration of model and process research. Research is needed to understand and characterize three types of model uncertainty: (1) internal, in which multiple runs of the same model give different or divergent results because of the stochastic nature of some model parameters or the mathematical representations within the model; (2) intermodel, which involves using ensemble runs to determine if different models give different or similar results; and (3) model observations, which address the divergence between model projections and recorded observations. Each of these uncertainties is important for understanding climate simulations and will require different approaches to resolve. In addition to ensemble comparisons, models need to be challenged with actual observations. This will require targeted research that provides information compatible with the spatial and temporal scales of current models and increased integration in the planning, execution, and analysis of climate-related research programs.

5. Understand Sign (+ or –) of the Carbon Feedback and How It Changes over Time

Global-scale modeling efforts have been used to simulate potential effects of climate change on ecosystems and their role in the global carbon cycle because of insufficient direct evidence describing such effects across multiple spatial and temporal scales. In general, model results show a wide range of terrestrial carbon cycle responses to warming. Direct observational and experimental evidence shows that processes controlling the storage and flux of carbon among the atmosphere, terrestrial, and ocean biospheres are sensitive to temperature, but the mechanisms are only partially understood. Changing climate—particularly as it relates to increasing temperature—is expected to alter the cycling and storage of carbon, resulting in feedbacks that further impact climate change. Unfortunately, there is not a broad consensus on whether this feedback has a positive or negative value. This leads to major uncertainty in our ability to project future climate. DOE has a long history of contributing to both the process and modeling components of understanding the carbon cycle and its feedbacks. DOE's ongoing contributions to the resolution of existing uncertainty require improving process-level understanding of terrestrial and atmospheric systems—including ecosystem-scale observations and experimentation—and incorporating these new insights into coupled models.

6. Understand Role of Natural and Anthropogenic Disturbances in Earth Systems and Incorporate This Information into Model Projections

Disturbance, both natural and anthropogenic, was recognized as a major factor in altering the balance of all Earth systems. Disturbances range from extreme natural events like fire, drought, major storms, and volcanic eruptions to anthropogenic land-use change such as urbanization, afforestation, and shifts in agriculture. Disturbances often dominate the long-term response of natural systems. However, the role of disturbance is neither well understood nor incorporated robustly into current ESMs. Experiments and modeling suggest that interactions with disturbance history, nutrient supply, and changes in temperature and soil moisture all can play significant roles in determining the magnitude and timing of carbon uptake by land ecosystems under increased CO_2. Among these factors, the role of disturbance is the least characterized and is thought to play an important role in ecosystem changes. The ability to distinguish among different disturbance types for differing ecosystems is critical for accurately incorporating these important factors into models.

7. Understand and Incorporate the Complete Water Cycle into Regional, Climate, Earth System, and Integrated Assessment Models

Water was recognized throughout the workshop as a critical integrating factor for climate projections and is an integrating factor for many Earth systems. The need to understand and incorporate the complete water cycle in regional, climate, Earth System, and Integrated Assessment models was identified as an important goal for the climate research community. Known challenges exist in representing water cycles in models of the physical climate system. Although there is some agreement among models on predicting large-scale patterns of future precipitation changes, regional shifts in water availability and hydrologic extremes still are difficult to predict. Nonetheless, precipitation and soil moisture are critical to human systems, ecosystem community structure, and carbon balance. Understanding and predicting water availability, seasonality, extreme events, and use for irrigation are important for more integrated insights into coupled Earth systems. In addition, subsurface water (i.e., groundwater) is poorly represented in most models and can be a controlling factor in many ecosystems. Incorporating water cycle considerations across BER's programs will enhance the systems approach to climate change research.

2.2 Summaries of Breakout Session Discussions

The following section provides summaries of the written and oral results of the workshop. The summaries are organized according to the workshop structure: disciplinary discussions in atmospheric science, terrestrial science, and climate modeling, as well as discussions of high, temperate, and tropical latitudes. Additional details may be found in subsequent chapters containing the full discussion papers.

Atmospheric Science

The Atmospheric Science group emphasized that the impacts of aerosols and cloud-aerosol interactions on climate, cloud responses, and associated radiative effects are among the greatest uncertainties in our ability to predict climate change. These processes and their impacts on the climate system also vary with the climate regime and are, in turn, impacted by interactions with the rest of the Earth system depending on latitude and geography.

Desired Outcome. *Understand and quantify the interplay among aerosols, clouds, and climate and determine the mechanisms responsible for cloud feedbacks in order to improve the reliability of future climate change predictions, with particular attention to the impact on Earth's radiative balance and precipitation.*

Approach. The Atmospheric Science breakout group identified three related but distinct areas of research in which advances are needed to achieve this outcome:

1. **Aerosols and their interactions with clouds.** The interactions between aerosols and clouds represent a critical area of uncertainty in climate change studies. A more precise understanding of these interactions is needed to interpret the impact that changing emissions resulting from shifts in energy sources and land use have on the chemical and physical properties of aerosols and on the combined influence on cloud properties.
2. **Cloud feedbacks.** Better characterization and quantification are needed of the mechanisms, radiative impacts, and signs of cloud feedbacks. Also needed are estimates of the regional magnitude and uncertainty of both shortwave and longwave cloud feedbacks.
3. **Improved strategies for high-resolution modeling.** Higher-resolution simulations, evaluated with observations on a similar scale, need to be performed. These simulations are necessary to expose the sensitivity of the energy and hydrological cycles and their interactions with clouds and aerosols to the resolution of models.

Near-Term Goals (1–3 years). Efforts should be continued to refine our understanding of and ability to predict atmospheric processes that control radiative flux between the top of the atmosphere and the boundary layer (i.e., clouds, aerosols, and related processes). Collection and use of long-term observational records from the ARM Climate Research Facility should be continued, expanded, and exploited. The resulting improvements in understanding need to be incorporated into process and global models. These models, in turn, must be evaluated iteratively against observational datasets, including those from the ARM Climate Research Facility.

Mid-Term Goals (4–7 years). Enhanced sets of observational data and process information should be used to test the fidelity of improved candidate physics modules (as well as current Community Earth System Model modules) in hindcast and case study mode. The ability of these modules to reproduce physical cloud properties and radiative effects for different aerosol and dynamical conditions needs to be documented, and predicted cloud feedbacks need to be determined over multiple scales. These test case results and refined observational and experimental process studies should be used to develop next-generation refinements to these model components. The sign, magnitude, and uncertainty of global shortwave cloud radiative feedbacks also need to be estimated.

Long-Term Goals (8–10 years). Models should be developed that are capable of representing aerosols, clouds, their interactions, and their impacts on precipitation and radiative budgets. Observational datasets specifically designed to evaluate the planned model advances must be developed and used. A series of simulations needs to be conducted with these models over a range of temporal and spatial scales to demonstrate and determine their improved ability to represent cloud properties.

Terrestrial Science

The Terrestrial Science group noted that terrestrial ecosystems store roughly four times more carbon than the atmosphere and that annual carbon fluxes between the terrestrial biosphere and the atmosphere are nearly seven times greater than annual anthropogenic carbon emissions from fossil-fuel combustion and land-use change. Thus, the carbon stored in long residence–time terrestrial sinks (e.g., wood and soil organic matter) has the potential, over time, to significantly impact the carbon balance in atmospheric reservoirs. The potential for rapid and large perturbations to these systems supports the need for quantitative understanding of the responses and feedbacks so that future climate change can be accurately predicted.

Desired Outcome. *Understand and quantify regionally specific effects of ongoing and future climate changes on the structure and functioning of terrestrial ecosystems, including feedbacks between ecosystems and the climate system, so that society can better understand, predict, and plan for climate change.*

Approach. The primary focus should be to obtain a detailed mechanistic understanding of ecosystem dynamics—including net land carbon flux—and the relationship to climate change factors. Important processes to include are net primary production, autotrophic respiration, heterotrophic respiration, and ecosystem changes due to disturbance. Focused research is needed on mechanisms that have strong interactions with climate change and are poorly constrained by theory and observation. This breakout group recognized that different mechanisms are likely to play dominant roles in different climate zones and ecosystem types. The group also noted that a key to deconvoluting these challenges is to target critical processes in different climate zones, and they identified key questions associated with specific latitudinal systems. Subsurface ecosystem mechanisms (e.g., biogeochemistry) also were discussed as particular areas of need well aligned with BER capabilities.

Near-Term Goals (1–3 years). Basic research and multifactor ecosystem manipulation experiments need to be conducted in the most climatically important and sensitive terrestrial ecosystems (e.g., the Arctic). Long-term observational programs such as AmeriFlux should be continued, expanded, and leveraged. Importantly, all of these efforts must be carried out in coordination with the needs and perspectives of the modeling community.

Mid-Term Goals (4–7 years). Model projections should be tested against initial results from the outlined experiments. The results can be used to improve process models and next-generation ESMs. As Arctic experiments progress, corresponding experiments should be initiated in a second priority ecosystem using lessons learned and scientific and modeling advances made in the interim. Observational datasets need to be expanded by enhancing the AmeriFlux network with model-informed data and analysis infrastructure to improve the synthesis, evaluation, and transfer of knowledge to ESMs. Interactions between ESM and process science communities should be continued to identify priority research needs in each discipline, with an emphasis on making regional estimations of ecosystem function and response.

Long-Term Goals (8–10 years). Results from Arctic experiments must be synthesized to improve process representations in state-of-the-art ESMs. Model projections should be tested against initial results from experiments in the second priority ecosystem. The resulting knowledge needs to be incorporated into relevant process models and next-generation ESMs. The AmeriFlux network should be updated based on the needs of and results from model sensitivity analyses and scientific and technological advances. A major synthesis of results from process research and ESM projections should be conducted to estimate ecosystem response at regional and global spatial scales and at decade to century time scales.

Climate Modeling

Models of Earth's climate system are mathematical tools that provide an integrated view of the planet's current and future climate. Improved through better understanding of relevant physical, chemical, and biological processes, these models increasingly represent and incorporate previously unaccounted physical, chemical, and biological mechanisms. However, the size, complexity, and sophistication of models of Earth's physical systems already exceed current computational capabilities. Additionally, demand has increased for reliable climate information on regional scales for a variety of aspects relevant to society.

Desired Outcome. *Develop and test an application-focused comprehensive Earth System Modeling capability and analysis environment that includes natural and human Earth systems, information on climate change at decade to century time scales and local to global spatial scales, and descriptions and quantification of uncertainties.*

Approach. The Climate Modeling breakout group identified four related but distinct areas of research that need to advance to achieve this outcome:

1. **Development of a comprehensive ESM.** Such a model would include physical, biogeochemical, and human-system components. The integrated model also would incorporate resolved dynamics; parameterizations of unresolved physical, chemical, and biological processes; and algorithms to couple submodels and component models.
2. **Development of a comprehensive, multiscale modeling capability that spans regional to global scales.** This effort is important because critical aspects of global climate change emerge through the rectification of processes occurring at spatial and temporal scales well beyond current modeling capabilities.
3. **Development of applications and environments for model evaluation.** Model projections must be evaluated by independent researchers. This requires participation of diverse groups of scientists who have expertise in observations and their quality and who are familiar with the applications of models and quantitative assessment of model strengths and weaknesses.
4. **Description and quantification of uncertainty in climate models.** Uncertainty needs to be described and quantified in each aspect of process understanding. The resulting understanding needs to be incorporated into models (at all scales) and into the projections of those models. BER research also should address model uncertainty as both an explicit and implicit part of determining priorities in the model development path.

Developing an ESM that can be used for projecting future climate change will involve a series of steps in which new processes and methods are continuously and incrementally added and tested. This includes informing model development with a cyclical process of observation, measurement, and experiment as part of the progression of model development, evaluation, and release.

Near-Term Goals (1–3 years). The Climate Modeling group identified a need to implement and evaluate the latest generation of ESMs while increasing emphasis on regional-scale modeling and the associated methodologies necessary for producing regional-scale resolution. Efforts should continue to provide physics-based representations of currently parameterized critical processes and to develop first-generation integrated ESMs. To advance our ability to evaluate models and assess their state of the art, the community should support organized simulation and analysis efforts, such as the Intergovernmental Panel on Climate Change (IPCC) and the Coupled Model Intercomparison Project (CMIP). Efforts should be made to identify and resolve critical biases identified by the analyses. An identified overarching need is to describe and quantify uncertainty in model projections. This will require developing, evaluating, and implementing new approaches to compare uncertainty from numerous perspectives.

Mid-Term Goals (4–7 years). Additional and improved process models need to be incorporated into coupled models (e.g., ESMs). Near-term advances in regional-scale modeling will be incorporated into ESMs, including improvements in time integration for managing multiple resolutions in the same model and better approaches for initializing simulations. Biases identified in previous evaluations should be addressed by improving existing process models or developing new models as appropriate. Next-generation ESMs using multiscale approaches that allow the regional evaluation of, for example, clouds and ocean eddies should be run and evaluated. Model evaluation should provide feedback to drive improvements in underpinning models. Previously developed approaches to uncertainty quantification should be applied to current simulations. Improvements in such quantification need to include a framework for evaluating regional-scale and comprehensive ESMs.

Long-Term Goals (8–10 years). State-of-the-art capabilities in process, regional, Integrated Assessment, and Earth System Modeling should be used to create a comprehensive and integrated ESM. This will include using state-of-the-art approaches that provide multiscale capabilities (nested regional to global modeling scales) and quantify uncertainty. This new capability should be used to initiate, evaluate, and iterate grand challenge simulations.

Latitudinal Opportunities for Integrated Research Efforts

High Latitudes. Discussions about challenges and opportunities for high-latitude research predominately centered on the current lack of long-term observational datasets and the important, but poorly understood, potential impacts of disturbance. The major conclusion was that most high-latitude systems are insufficiently observed, understood, and represented in global models. The concept of polar amplification was stressed (i.e., alterations of climate-related, high-latitude systems may have significant global implications, such as sea-level rise from melting ice or massive carbon release from thawing permafrost). This is complicated by the fact that understanding of temperate-latitude systems does not translate well into understanding of high latitudes (e.g., clouds and ice nucleation and interactions among sea ice, land ice, and snow). There are also unique biomes and interfaces, such as biogenic activity around permafrost or sea ice, that can be studied only in high-latitude systems. Identifying and investigating major disturbance regimes (e.g., changing snow and ice coverage, fire, and warming) were seen as the best ways to prioritize research efforts. Positive feedbacks with likely significant impacts include: albedo–temperature–water cycle feedbacks from warming; the magnitude and nature of carbon releases from melting permafrost; and external (anthropogenic) radiative forcing exerted on the Arctic, including cloud cover, black carbon, ozone, sulfate, greenhouse gases, and organic carbon aerosols.

Examples of global-scale, overarching research challenges in high-latitude systems include:

- Determining the consequences throughout the system of a seasonally ice-free Arctic, including impacts on terrestrial and marine ecosystems, permafrost thaw, atmospheric circulation, cloud formation, and aerosol availability and type.
- Assessing the potential predictability (and how to realize that predictability) of the Arctic system on different time scales.
- Identifying and characterizing tipping points and abrupt changes.
- Understanding the role of extreme events on the trajectory of the system.

In addition, group members acknowledged that process research in areas currently not part of the

BER program is needed because such studies will inform BER modeling efforts. These include cryospheric and oceanographic processes associated with the Arctic, particularly in light of the emergence of ice-free water. Such research would require engaging other federal agencies that support climate science. Overall, high-latitude research efforts are challenged by the remoteness of these systems, the extreme conditions under which observations and experiments need to be performed, and the international nature of the Arctic system in particular.

Temperate Latitudes. Because they have the largest populations, temperate latitudes were highlighted as the locations where humans will be impacted most by climate change. Temperate regions also are home to major sources of greenhouse gas emissions, are the most studied and observed areas, and thus are the latitudes of greatest understanding and data density. A high priority is to synthesize existing temperate-latitude ecosystem and climate process studies—an effort that will advance Earth System Modeling. The role of the water cycle and the impacts of a changing climate on the water cycle also were seen as important research objectives. Although not unique to this latitude, the importance of the water cycle was highlighted as an integrating approach that encompasses many critical aspects of climate research: ecology, cloud processes, and aerosols. The modeling community sees temperate latitudes as crucial for the movement of water from tropical to high latitudes. Temperate latitudes are where human impacts are generated and where changes probably will have the greatest direct effects (e.g., water availability and agriculture). The richness of available datasets from this region argues for intensive analysis and evaluation of regional-scale prediction capabilities with optimal science input. An example would be to conduct sensitivity studies of process climate modeling over a continent. The concentration of human impacts in this latitudinal band points to the potential for the human dimension to dominate other forcing factors, including the ability to predict how the entire Earth system would respond to anthropogenic interventions such as geoengineering or cap-and-trade measures.

Examples of cross-disciplinary research emphasized for temperate latitudes include: (1) aerosol fertilization of extensive temperate forests and generation of secondary aerosols from these forests, (2) aerosol indirect effects and cloud feedback effects, and (3) the need to close the temperate-latitude carbon budget.

Tropical Latitudes. The tropics (the area between ± 23.5 degrees latitude) represent approximately 40% of Earth's land surface area. However, this geographical location is thought to be responsible for a disproportionately large number of known model biases. Coordinated efforts are needed to understand and incorporate the roles of tropical ecosystems into models and to determine how these roles are likely to change as a result of human activities. Major model deficiencies with regard to tropical processes include El Niño–La Niña-Southern Oscillation (ENSO), Inter Tropical Convergence Zone (ITCZ), Madden–Julian Oscillation (MJO), and monsoon and precipitation features. Workshop participants noted that these deficiencies are the same areas the research community would have listed a decade ago—an observation highlighting the scientific challenges inherent in such processes.

The water cycle was seen as a critical factor for understanding these and other integrated tropical processes. This cycle also is a dramatically understudied aspect of diverse systems, including cloud processes, rainfall seasonality, and soil moisture. Because it links terrestrial and atmospheric processes, the water cycle is a potential integrating factor for BER climate research programs. From a modeling perspective, efforts to link models across scales are another mechanism to integrate process and modeling science. Scaling and information exchange also are viewed as critical research challenges.

There is a need to reconcile the various components of the global carbon budget and to be able to predict the future of the tropical carbon sink. This includes important integrating research topics such as understanding and modeling forest and savannah transitions with respect to water and nutrient cycling, aerosol production, and biogenic organics. A coupled carbon-water tropical research program could engage the full spectrum of BER climate science and provide critical advances to process science and ESMs. Fire, although not unique to tropical systems, is a critical and often underrepresented factor in modeling ecosystem structure, carbon cycling, and aerosol production. The impact of land-use change (particularly deforestation and irrigation) is a major crosscutting issue with broad climate implications for the tropics. Opportunities exist to establish common research infrastructures in the tropics, including coordinating the establishment of long-term observational platforms with large-scale manipulative experiments. Individual-investigator research in tropical systems should be encouraged as a step toward potential larger-scale efforts in the future.

3. Atmospheric Science Discussion Paper

Understanding and Quantifying the Interplay among Aerosols, Clouds, and Climate

3.1 Current Situation

General circulation models (GCMs) are complex, integrative tools that rely heavily on parameterizations of the physical processes of the climate system. Although today's GCMs are far superior to those from a decade ago, the range of climate sensitivity values from these models has not decreased significantly with time. A major challenge in current climate research is understanding the effects of aerosols and cloud-aerosol interactions on climate as well as the cloud response and radiative impact associated with changing greenhouse gas forcing and aerosols. As documented in assessments by the Intergovernmental Panel on Climate Change (IPCC) and others, these two areas represent the greatest uncertainties in quantitatively predicting climate changes and their impacts, such as shifts in regional precipitation. For example, although there is some agreement among models on predicting large-scale patterns of future precipitation changes, regional shifts in water availability and hydrologic extremes still are difficult to predict.

Cloud extent and lifetime, as well as precipitation amount and intensity, are strong yet complex functions of the environment in which clouds and precipitation form. These environmental factors include aerosol loading, composition, and particle size as well as the small- and large-scale dynamic and thermodynamic state of the atmosphere. The uncertainty in cloud response to external forcings impedes the ability to understand how climate has and will be influenced by changes in the emission of greenhouse gases, aerosols, and their precursor gases and by the associated cloud feedbacks.

Our understanding of atmospheric processes has increased greatly over the last decade because of improved observational and laboratory capabilities and the use of high-resolution process models (e.g., large eddy simulation models and cloud-resolving models). However, this new knowledge has been incorporated slowly into GCMs because of the complexity of the processes and the difficulty in representing that complexity in models that can treat the processes only parametrically. Moreover, our knowledge is incomplete in many areas, particularly (1) the interactions between clouds, small-scale dynamics, and the large-scale atmospheric state; (2) processes occurring at the molecular scale that influence aerosol and cloud-droplet formation and ice nucleation; and (3) aerosol-chemistry-cloud interactions and precipitation scavenging.

The large-scale atmospheric state has strong regional dependence, especially as it relates to aerosol and cloud properties. Cloud feedbacks and aerosol effects—including direct light scattering and impacts on clouds—then may be expected to be climate regime dependent and will interact with the rest of the Earth system in complicated ways at different latitudes and over different types of surfaces.

3.2 Inputs and Resources

The atmospheric research programs within the Department of Energy's (DOE) Office of Biological and Environmental Research (BER) have a proven history of providing cutting-edge science for understanding anthropogenic influences on climate. BER atmospheric research is focused on developing a sufficiently detailed and accurate understanding of aerosols, their interactions with clouds, and the subsequent impact on climate so that models incorporating these processes will have substantially less uncertainty in their predictive capabilities than do current ones.

BER has a wide range of resources being used to address the outstanding questions in atmospheric systems research. These include:

- Complex physically based atmospheric models spanning a wide range of scales, from the local to global.
- Extensive atmospheric datasets on aerosols, clouds, radiation, and precipitation acquired in the past 1 to 2 decades. These datasets include ground-based remote sensing data, satellite data, and *in situ* data from aircraft, unmanned vehicles, and balloons.
- The ability to collect additional data for targeted problems through long- and short-term field experiments using Atmospheric Radiation Measurement (ARM) Climate Research Facility fixed sites, ARM Mobile Facility campaigns, and ARM Airborne Facility missions.
- New techniques for measuring broad categories of the composition of aerosols and their precursors.
- New experimental laboratory systems and approaches for studying the formation and fates of aerosols under atmospheric conditions and their role as cloud condensation nuclei (CCN) and ice nuclei (IN).
- A proven capability to integrate the results of laboratory and field studies into state-of-the-art models on a variety of geographical and temporal scales.

These resources—both intellectual and physical or infrastructural—are distributed among many entities, including DOE national laboratories such as Pacific Northwest National Laboratory (and the DOE Environmental Molecular Sciences Laboratory), Argonne National Laboratory, Oak Ridge National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, Los Alamos National Laboratory, and the National Renewable Energy Laboratory. Additional participants are other governmental agencies like the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration (NASA), and Environment Canada; U.S. and international universities; and other research institutes (e.g., the National Center for Atmospheric Research). This breadth of participants and resources provides a unique and powerful springboard to generate new and transformative insights into aerosols, clouds, and their interactions, as well as cloud dynamics and their impacts on climate.

3.3 Desired Outcome

DOE, as the steward of U.S. energy policy, has sponsored research aimed at improving the representation of a wide range of atmospheric processes in GCMs to advance the fidelity of these models. In the next decade, BER will focus on understanding and quantifying the interplay between aerosols, clouds, and climate and the mechanisms responsible for cloud feedbacks. This knowledge will help improve the reliability of predictions of future climate change, with particular attention to impacts on radiative balance and precipitation. To accomplish this goal, the problem will be separated into three subobjectives:

1. **Aerosols and Their Interactions with Clouds.** The interaction between aerosols and clouds is a critical area of uncertainty in climate change studies (past and future). A more precise understanding of these interactions is needed

to interpret how changing emissions (of aerosols, their precursors, and greenhouse gases) resulting from shifts in energy sources and land use affect the chemical and physical properties of aerosols and the combined influence on cloud properties.

2. **Cloud Feedbacks.** Better characterization and quantification of the mechanisms and radiative impact of cloud feedbacks are needed. This includes the signs and estimates of the regional magnitude and uncertainty of both shortwave and longwave cloud feedbacks.
3. **Improved Strategies for High-Resolution Modeling.** Such strategies will involve performing higher-resolution simulations, evaluated with observations on a similar scale, to expose the sensitivity of the energy and hydrologic cycles—and their interactions with clouds and aerosols—to the model resolution. These studies will include land surface models of vegetation, storage, and run-off; atmosphere-cryosphere interactions; processes affecting changes in extreme weather events; and interactions between cloud- and large-scale circulations.

The near-, mid-, and long-term goals associated with these subobjectives are given below to provide one possible roadmap for how each could be accomplished. Although clearly interrelated with multiple connections, these subobjectives are discussed separately in this chapter to maintain roadmap clarity.

Aerosols and Their Interactions with Clouds

Aerosols and their interactions with clouds are responsible for major uncertainties in characterizing climate change over the last 150 years. Anthropogenic sources for aerosols and their gaseous precursors have changed dramatically over this period as emissions associated with fossil fuel, land use, and agriculture have changed. Uncertainty in the response of clouds to aerosol changes (in terms of changes in cloud reflectivity, extent, and lifetime and in precipitation amount and intensity) has complicated our understanding of how the Earth system has responded to changes in greenhouse gases during the past century. The uncertainties introduced in interpreting this driving agent of climate change impede our ability to understand how changes in other such agents (like greenhouse gas emissions and cloud feedbacks) have and will influence climate. For this reason, the climate research community needs to intensify its efforts to (1) provide a quantitative understanding of aerosol influence on clouds and climate and (2) reduce uncertainties associated with the impacts of anthropogenic emissions of aerosols (and their precursors) on climate.

Near-Term Goals (1–3 years)

- Identify a set of case studies (with boundary-condition and evaluation datasets) for large eddy simulation (LES) modeling appropriate for studying aerosol-cloud interactions in different synoptic and climatic regimes. While several previous Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) activities have attempted to compare the behavior and realism of LES models, these studies have not attended sufficiently to the role of aerosols in LES response.
- Analyze output from the IPCC's Fifth Assessment Report (AR5) for the range of described emission scenarios to characterize and understand the various responses to aerosols from the different climate models employed.
- Improve our understanding of aerosol impacts on clouds using a mixture of ARM advanced data products and fixed-site observations (augmented by instrumentation funded by the American Recovery and Reinvestment Act), ARM Mobile Facility and ARM Airborne Facility deployments, laboratory studies, and satellite data. This goal includes ascertaining the important chemical, physical, and structural properties of aerosols that determine their CCN/IN activity.
- Conduct laboratory and field experiments to elucidate the major precursors of aerosols and the important oxidants and mechanisms leading to aerosol formation.
- Design field and laboratory experiments to measure the indirect effect of aerosol changes on cloud fields, including perturbations introduced into the aerosol field in the vicinity of clouds.

Mid-Term Goals (4–6 years)

- Comprehensively characterize aerosol formation and chemical evolution. Such characterizations will require demonstrating an understanding of the chemistry involved and an ability to predict, for example, aerosol size distribution, optical properties, and CCN/IN activity given a set of precursor gases and aerosol emissions and a set of meteorological conditions in the vicinity of the emission region (prior to cloud processing).
- Statistically describe the macro- and microphysical properties of clouds for different aerosol, dynamical, and thermodynamical conditions—separating the statistics by some sort of classification scheme and different climate regimes.
- Demonstrate that LES models correctly simulate cloud and precipitation response to clean versus polluted conditions in different dynamical and thermodynamical environments.
- Determine the interplay among gases, aerosols, and aqueous chemistry that occurs in clouds and the subsequent impact these interactions have on aerosol properties (i.e., cloud effects on aerosols).

Long-Terms Goals (7–10 years)

- Construct an observationally based dataset of cloud and aerosol properties over a range of dynamical and thermodynamical conditions. This dataset must allow separation of aerosol impacts from the influence of meteorological variability on cloud properties to understand the relative importance of these factors.
- Demonstrate that models can properly simulate cloud properties in both aerosol-perturbed and -unperturbed conditions. In other words, show that a model can separate the meteorological versus aerosol influence on clouds in short-term episodes over a range of different meteorological regimes and cloud types.
- Implement parameterizations of appropriate aerosol-cloud interactions in climate models.
- Produce models capable of projecting aerosol influence on clouds and precipitation and the impact on the radiative budget that is relevant for climate change studies.

Cloud Feedbacks

Approximately 20 years ago, cloud feedbacks were identified as fundamental drivers of differences among simulations of climate change produced by different models subject to the same climate forcing. Today, we have accurate, decade-long, top-of-atmosphere (TOA) fluxes from CERES (NASA's ongoing Clouds and the Earth's Radiant Energy System experiment) and accurate surface fluxes from a collection of surface sites. The computed atmospheric shortwave absorption values—when TOA and surface fluxes are matched in space and time for short time periods of an hour to a day—are wildly variable and inconsistent with our theoretical understanding of atmospheric radiative transfer. Clouds and their interaction with shortwave radiation are deemed to be the causes of this problem. Understanding and resolving this challenge represent a fundamental step toward knowing how clouds affect Earth's radiation budget.

Given the relatively short period of satellite observations and the natural variability of the climate system, observing cloud feedbacks associated with slow climate forcing—such as the increase in greenhouse gas concentrations—is not yet possible. However, we can observe changes in cloud properties and associated changes in cloud radiative impacts in response to observed shifts in short-term internal climate dynamics (such as the El Niño-Southern Oscillation and Madden–Julian Oscillation in the tropics) or seasonal changes in ice cover in the polar regions. Gaining this information requires explicitly retrieving cloud optical and microphysical properties and relating the variability in these properties within a climate regime to the thermodynamic and dynamic variability in atmospheric circulation on the regional scale. The climate research community needs to develop appropriate methodologies—usable in both the current atmosphere and in model simulations of the current atmosphere—for evaluating the ability of GCMs to adequately represent cloud radiative effects and their response to circulation changes on a short time scale. Additionally, the climate modeling community needs to coalesce behind a methodology (or possibly a few methodologies) to assess cloud feedbacks in models so that (1) each model can be subjected to the same analysis and (2) comparisons among model representations of cloud feedbacks can be simplified.

Near-Term Goals (1–3 years)

- Improve our understanding of the relationship between observed TOA and surface radiative fluxes and their dependence on cloud structure and optical properties.
- Converge on a methodology to assess cloud feedbacks in GCMs and to relate observed changes in the properties and radiative effect of clouds to changes in circulation properties.

Mid-Term Goals (4–6 years)

- Observationally relate the radiative effect of clouds, in both the shortwave and longwave, to variability in cloud properties and environmental conditions. This evaluation must be carried out as a function of climate regimes, paying particular attention to the ones where clouds play a dominant role in determining the regional radiation budget, such as the Arctic and marine stratocumulus regimes.
- Assess cloud radiative impacts and their response to short-term (annual to decadal) circulation variability in the AR5 models and provide a quantitative evaluation of these quantities compared to observations of the current climate as a function of climate regime.

Long-Term Goals (7–10 years)

- Determine the sign and magnitude, within a factor of 2, of the global shortwave cloud feedback.
- Demonstrate that global climate models can simulate changes in cloud structure, optical properties, and radiative effects consistent with the variability and change in circulation and sea surface temperature over the last 20 years.

Improved Strategies for High-Resolution Modeling

Because cloud and cloud-aerosol interaction processes operate on small scales, higher-resolution regional models, cloud-resolving models (CRMs), and LES models increasingly are being used to address specific questions about cloud processes. In most case studies, models have disagreed markedly among themselves and relative to observations because of different parameterizations of ice-phase and mixed-phase microphysics, turbulence on subgrid scales, and the resolution and domain size used. Climate models produce information at coarse scales, but many applications of practical interest require smaller-scale information on statistics of quantities like precipitation. Various statistical and dynamical downscaling techniques have been developed for this purpose, with no approach being clearly preferable. A different category of downscaling is the multiscale modeling framework approach that embeds a coarse CRM within each gridbox of a global climate model to replace the parameterizations of clouds and convection. These models have shown some skill in deep convective regimes, but their usefulness in other climate regimes must be explored more fully. A single approach to downscaling likely will not be ideal in all situations (e.g., simulating hurricanes versus simulating local precipitation statistics to drive a hydrologic model). An optimized approach to downscaling might allow some fundamental questions to be addressed about cloud feedbacks and their impact on general circulation and regional climate change before conventional GCMs or global CRMs are able to tackle such issues. The community needs to undertake a systematic study of high-resolution models and their relationship to global models to accelerate progress toward realistic climate change prediction.

Near-Term Goals (1–3 years)

- Develop observationally based datasets—including both boundary conditions and observations of atmospheric, aerosol, and cloud properties—that can be used to drive and evaluate CRM simulations of clouds and precipitation. Specific attention needs to be paid to developing datasets in currently underrepresented climate regimes such as tropical land areas and polar regions.
- Elucidate the precursors responsible for new particle formation and growth in air to evaluate how dependent these processes are on region and scale.

Mid-Term Goals (4–6 years)

- Improve representation of cloud microphysics, cloud-turbulence interactions, and surface fluxes in CRMs to the point that these models faithfully reproduce cloud and precipitation features in observed case studies.

- Carry out long-term (seasonal to multiannual) CRM simulations at fixed ARM Climate Research Facility or ARM Mobile Facility deployment sites to test the ability of CRMs to simulate cloud processes and surface-atmosphere interactions accurately for a diverse set of meteorological conditions.
- Conduct comparison studies of downscaling techniques and models for a set of regions spanning different climatic zones (e.g., tropics to Arctic) and evaluate the relative and absolute skill of each.
- Identify the time and geographical scales over which aerosol properties determining CCN/IN activity change in different climate regimes to provide data relevant to higher-resolution models.

Long-Term Goals (7–10 years)

- Assess downscaling techniques and—based on climate regime and requirements of different user communities—converge on the accuracy and utility of various approaches.
- Carry out long-term (decadal to century) simulations for the past and current centuries for different climate regimes to understand the efficacy of these approaches. Also address outstanding questions about determinants of regional climate—including aerosols and their interactions with clouds—emphasizing impacts on the hydrologic cycle and extremes.

4. Terrestrial Science Discussion Paper

4.1 Current Situation

Terrestrial ecosystems provide irreplaceable services to humanity through production of food, fiber, and fuel. Understanding and predicting the effects of climate change on terrestrial ecosystems are therefore critically important to society. Terrestrial ecosystems also play several fundamental roles in the dynamics of Earth's climate system and its response to changes in atmospheric composition, radiative forcing, and land surface properties. They store about four times more carbon than the atmosphere, and annual carbon fluxes between the terrestrial biosphere and atmosphere are nearly seven times greater than annual anthropogenic carbon emissions from fossil-fuel combustion and land-use change. Since terrestrial ecosystems react rapidly to perturbation, the response of land surface properties and land carbon pools and fluxes to climate change can generate important feedbacks that could accelerate such change on short (decadal to century) time scales. Thus, a quantitative and predictive understanding of these responses and feedbacks is necessary for accurately predicting future climate change. Understanding climate system feedbacks and their influence on the ability of terrestrial ecosystems to continue providing essential services under a changing climate is necessary for informing effective climate change mitigation and adaptation policies.

Climate change encompasses a broad spectrum of factors, many of which can generate significant ecosystem responses. The most important climate factors—in terms of influence on unmanaged ecosystems and the carbon cycle—are changes in carbon dioxide (CO_2) concentration; temperature; the frequency, intensity, seasonal patterns, and annual mean accumulations of precipitation; cloud cover and downwelling radiation; humidity; atmospheric inputs of reactive nitrogen; near-surface ozone concentrations; and atmospheric inputs of black carbon aerosols. These factors, however, do not operate in isolation. Experimentation and modeling studies suggest that ecosystem responses depend strongly on interactions among forcing factors. They also depend on interactions within ecosystems among carbon and nutrient cycles, hydrology, disturbance dynamics, age-class distributions, community structure, physiology, and physiological adaptation.

Observation, experimentation, modeling, and synthesis all have contributed to our understanding of how climate change influences terrestrial ecosystems and the carbon cycle. Our most complete knowledge relates to impacts that single factors of climate change forcing have on ecosystems in the temperate zone. The responses of tropical and high-latitude ecosystems to individual climate change factors still are poorly characterized, and the integrative effects of multiple, simultaneous climate forcings are not well understood even for the best-studied ecosystems in the temperate zone.

Experiments on ecosystem response to elevated CO_2 concentration consistently show short-term increases in net primary production, with less-consistent evidence that longer-term responses are mediated by carbon-nutrient interactions. Modeling studies hypothesize that global-scale response of land ecosystems to rising CO_2 is regulated strongly by carbon-nutrient interactions—a result with important consequences for predicting mean global CO_2 concentrations under a range of future scenarios. Experiments and modeling suggest that interactions with disturbance history, nutrient supply, and changes in temperature and soil moisture all can play significant roles in determining the magnitude and timing of carbon uptake by land ecosystems under increased CO_2. These interactions also are expected to have varying effects depending on the type of climate zone and vegetation community involved. Different plant species respond differently to elevated CO_2, leading to possible changes in the presence and abundance of species and subsequent effects on surface energy balance, hydrology, and productivity.

Although rare, some temperature and rainfall manipulation experiments also have explored the effects of climate change on terrestrial ecosystems. For example, temperature manipulations (e.g., using passive and active heating technologies and soil or whole-system heating) have shown significant (albeit not always consistent) responses in both primary production and heterotrophic respiration—two dominant processes controlling the net rate of ecosystem carbon exchange. In general, these results highlight the importance of soil moisture status and nutrient dynamics in regulating ecosystem response to warming. However, since most such work has been conducted in the temperate zone, virtually no data exist from tropical or high-latitude ecosystems. Similarly, data from precipitation manipulation experiments have shown variable results. For example, data from mature temperate forests suggest that these ecosystems may be resistant to long-term drought, but meta-analyses from tropical forests indicate that their net carbon exchange is sensitive to large-scale and long-term drought. Together, these studies underscore potential variations in the effects of climate change among different ecosystems and climate zones.

Observations of carbon, water, and energy fluxes and associated measurements of ecosystem processes currently are being conducted at dozens of U.S. locations as part of the AmeriFlux network, which is supported by the Department of Energy's Office of Biological and Environmental Research (BER) and other governmental agencies. The longest-running stations now have gathered nearly 20 years of observations, and many others have records longer than 10 years. Recent synthesis efforts have focused on multisite and multimodel evaluation exercises, resulting in important improvements in the consistency of station data records and the identification of critical knowledge gaps and prediction deficiencies in several models.

Mechanistic studies are explaining internal ecosystem feedbacks connecting carbon and ecosystem dynamics, but a more comprehensive understanding of the relevant processes is necessary to inform prediction and policymaking. For example, in all ecosystems, nutrient availability influences leaf physiology, plant carbon-allocation patterns, and decomposition dynamics, but significant interactions among nutrient cycles remain unresolved. Nitrogen fixation, for instance, has important mechanistic links to the phosphorus cycle, but no hypothesis testing of these interactions has yet been conducted. Similarly, both the type of disturbance and the time since its occurrence influence nutrient dynamics and carbon-nutrient interactions. Allocation patterns show age dependencies and pseudoperiodic behavior, but the mechanisms involved are not yet well understood. Mortality is connected to climate change factors through physiological stress; damage from insects and disease; and severe weather events such as drought, hurricanes, windstorms, and ice damage. Plants are adaptable to changes in their growth environment, and acclimation might occur under climate change, but mechanistic understanding of these dynamics is still weak. As a final example, carbon balance and ecosystem processes below ground are not understood as well as those above ground.

New insights on microbial community composition and function are emerging, but knowledge still is limited about mechanistic relationships to decomposition rates, nutrient dynamics, and soil organic matter stability. Acclimation of microbial activity and decomposition in response to climate change is increasingly well documented, but our understanding of the factors underlying thermal adaptation in soil microbial communities is lacking. In addition to new mechanistic studies, synthesis and meta-analysis efforts urgently are needed to organize and consolidate new knowledge gained from previous scientific investments.

Global-scale modeling efforts have been used to simulate potential effects of climate change on ecosystems because of insufficient direct evidence describing such effects across multiple spatial and temporal scales. In general, model results show a wide range of terrestrial carbon cycle responses to warming. Within a given model, variations arise by climate zone. Among models, they emerge because of the balance of factors influencing production and respiration and the influence of predicted climate change–induced shifts in plant communities. Models that include carbon-nutrient dynamics predict much different responses to climate change than those that do not, with the former suggesting less carbon release or even modest carbon uptake in response to warming. In all cases, however, ecosystem response to climate change appears to be strongly modulated by changes in soil moisture or nutrient dynamics. Today's models also tend to overestimate the severity of drought response in temperate and tropical forests. Current modeling results have helped to frame and refine a set of critical science questions regarding interactions between ecosystems and the climate system:

- Which factors control changes in CO_2 fertilization response on decadal to century time scales?
- How do carbon-nutrient interactions modulate the response of different ecosystems to warming?
- What role does changing soil moisture status play in the expression of long-term climate-ecosystem feedbacks?

Answers to these questions should be sought with new manipulative experiments and associated process studies.

In summary, a combination of observational, experimental, modeling, and synthesis efforts has greatly improved our understanding of the potential effects of climate change on terrestrial ecosystems. Despite this progress, our current understanding suffers from two very significant shortcomings. First, most experimental studies have focused on ecosystem effects of single factors of climate change forcing. Nearly all the work completed to date, however, highlights the importance of interactions among global change drivers, suggesting that investigating the effects of single drivers in isolation is insufficient. Second, most efforts have concentrated on ecosystems in the temperate zone. Tropical and high-latitude ecosystems, though, dominate global terrestrial carbon pools and fluxes, and their potential responses to even individual climate change factors still are poorly characterized.

An integrated research program is seen as the most effective means of advancing our understanding of land ecosystem response to climate change and of the associated climate-ecosystem feedbacks. Such a program would combine new, multifactor experimentation; novel mechanistic studies at high latitudes and in the tropics; synthesis of observations and experimental results; and continued evaluation and improvement of predictive models.

4.2 Inputs and Resources

The terrestrial ecosystem research community has decades of experience conducting field-scale experiments on ecosystems and the climate system and developing and evaluating models of their dynamics for application at multiple spatial and temporal scales. Systematic measurements of carbon, water, and energy fluxes and associated ecosystem variables have been made at multiple locations for more than a decade. Such long-term measurements are critical to understanding the dynamics of ecosystems and their potential responses to and feedbacks with climate change on decadal and longer time scales. BER supports a research community capable of carrying out complex, goal-oriented ecosystem research and modeling activities necessary to inform Earth System Models (ESMs) and decision makers concerned with the potential ecological effects of climate change.

First-generation ESMs are now operational. In addition to the traditional representation of physical climate system dynamics, the most sophisticated of these models include a predictive representation of carbon cycling in the terrestrial biosphere, oceans, and atmosphere. They also incorporate dynamic fire and biogeography, the land nitrogen cycle, and multiple trophic levels and nutrient limitations in oceans. Currently under development, second-generation ESMs introduce the dynamics of changes in land use and land cover in response to physical and biogeochemical factors associated with climate change.

4.3 Desired Outcome

Objective of the terrestrial science research activity:

To understand and quantify regionally specific effects of ongoing and future climate changes on the structure and functioning of terrestrial ecosystems—including their feedbacks with the climate system—so that society can better understand, predict, and plan for climate change and its effects on ecosystems.

Detailed mechanistic understanding of ecosystem dynamics (including the net flux of land carbon) and the relationship of these dynamics to climate change factors is a primary focus for this research. Important processes are net primary production, autotrophic and heterotrophic respiration, and ecosystem changes arising from disturbance. Focused research directed toward ecosystem mechanisms that interact strongly with climate change and are poorly constrained by theory and observation will result in improved understanding and more accurate prediction. Some of these critical mechanisms identifiable today include the influence of multifactor climate change on plant and microbial physiology, regional understanding of carbon-nutrient dynamics and coupled biogeochemical cycles, interactions between plants and microbial communities, disturbance dynamics, and biogeographical shifts in species distributions. Other critical mechanisms may emerge over the coming decade, and BER's Terrestrial Ecosystem Science activity should be configured to respond flexibly to new knowledge and insights.

Differing mechanisms likely will play dominant roles in different climate zones and ecosystem types. Research efforts must capture these critical variations, emphasizing the climate zones and ecosystem types that have the greatest impact on the global climate system. High-latitude systems with large stocks of soil carbon and tropical forests with large stocks and with high gross fluxes of carbon are the highest priority. This emphasis is needed partly because of our poor understanding of the critical climate-ecosystem mechanisms in these systems. In high-latitude systems, we must improve understanding of permafrost and thermokarst dynamics and how they relate to CO_2 and methane (CH_4) release under a changing climate. Seasonal freeze-thaw and snow cover dynamics in these systems also generate important climate effects through changes in surface energy fluxes and albedo. In tropical forests, a better understanding is needed of ecosystem sensitivity to rising CO_2, warming, and drought and how multiple nutrient limitations might constrain these responses. Climate change also could impact the energy balance in tropical forests, with potentially significant feedbacks to regional cloud cover and precipitation. Another high priority is improved understanding of interactions among disturbance history, CO_2 fertilization, nitrogen deposition, and climate change in temperate-zone forests. Some critical uncertainties extend across latitudinal boundaries. For example, plant-microbe interactions and soil organic matter dynamics, acclimation of plant physiological processes to climate change factors, predictive representation of plant mortality, and variation in allocation patterns in response to multiple forcings all have important sensitivities to climate change and are poorly understood or understudied.

Near-Term Goals (1–3 years)

- Design, prototype, and deploy a multifactor CO_2 × warming × nutrient manipulation study in a high-latitude, high-carbon permafrost environment. Perform *a priori* modeling.
- Perform feasibility studies for a new suite of moderate-cost tropical forest experiments focusing on multiple nutrient limitations and manipulations of CO_2, precipitation, and soil-only warming. Identify the most tractable experiments for deploying on short time frames, perform *a priori* modeling, and initiate experiments.

- Conduct comprehensive syntheses and meta-analyses of results from prior observational (e.g., AmeriFlux) and experimental (e.g., Free-Air CO_2 Enrichment) studies. Use results for multimodel evaluation exercises and for designing a formal, long-term network for ecosystem flux measurements.
- Evaluate the influence of disturbance history on net carbon exchange using existing flux networks as starting points. Use modeling to control for the large number of other factors that also contribute to variability in measured fluxes.
- Redesign the AmeriFlux network to introduce a manipulation component and to be driven by science questions relevant to BER. Add value to the national effort through coordination with the National Ecological Observatory Network.
- Design and initiate new process studies focused on soil organic matter dynamics and plant-microbe interactions.
- Devise and conduct model application studies focused on identifying single and multifactor climate–carbon cycle responses and feedbacks.

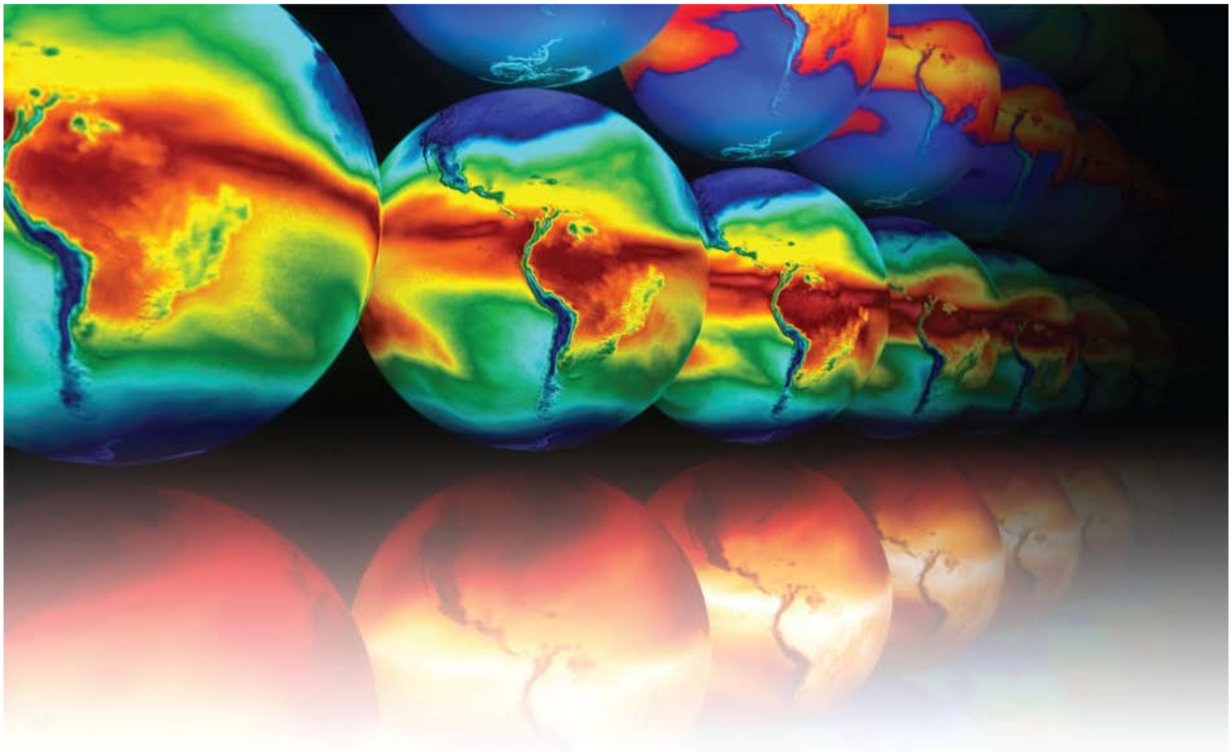
Mid-Term Goals (4–7 years)

- Continue the high-latitude, multifactor experiment. Perform an early evaluation of *a priori* model predictions against results.
- Select and initiate moderate-cost tropical forest experiments and synthesize their early results. Design, prototype, and implement coupled nitrogen-phosphorus models based on early hypotheses and experimental results. Perform *a priori* modeling.
- Incorporate into ESMs new process knowledge on the influence of ecosystem manipulation and disturbance history and on ecosystem interactions with climate and biogeochemistry. This knowledge will be gained through synthesis of experimental results and flux network activities.
- Implement the new AmeriFlux network focused on critical science questions and expanded to include experimental manipulations. A data and analysis infrastructure should be in place from the outset to facilitate data-model fusion, model evaluation and improvement, and effective acquisition and transfer of new knowledge to ESMs.
- Design and implement for ESMs a new generation of soil organic matter submodels based on synthesis efforts and new process studies.
- Continue model application studies focused on identifying single and multifactor climate-ecosystem responses and feedbacks. Initiate high-resolution simulations driven by the best available retrospective and future scenario datasets to explore regional details of ecosystem response and climate–carbon cycle feedbacks.

Long-Term Goals (8–10 years)

- Synthesize results emerging from the high-latitude, multifactor experiment and integrate them as new algorithms and improved parameterizations into a high-resolution ESM.
  - Position the program to answer the questions: How significant might effects of climate change be on Arctic tundra, and how important might feedbacks mediated through CO_2 and CH_4 releases and albedo changes be to regional and global climate?
- Synthesize results from moderate-cost tropical forest experiments and integrate the findings as new algorithms and parameterizations into a high-resolution ESM.
  - Position the program to answer the question: *What effect does multinutrient limitation have on the response of tropical forest ecosystems to climate change?*
- Update the long-term ecosystem flux measurement network to include new process measurements and manipulations, as suggested by model sensitivity analyses and synthesis of new observational and experimental work.
  - Answer the question: *What are the quantitative bounds of uncertainty for predicting ecosystem structure (states) and function (fluxes) using our best ecosystem models, as evaluated against observations across a range of ecosystem types and climate zones?*

- Develop and distribute a synthesis statement on ecosystem response to climate change and climate system feedbacks estimated at global and regional scales. This statement will be based on full analysis of results from process research and projections from improved ESMs informed by the research.
  - Answer the question: *How do feedbacks between terrestrial ecosystems and climate change factors influence predicted climate states on decadal and century time scales?*



5. Climate Modeling Science Discussion Paper

Developing Predictive Capabilities to Understand the Sensitivity of Earth's Climate System to Natural and Human Influences

5.1 Current Situation

Models of the Earth's climate system are among the most important tools scientists have for improving understanding of climate variability and change, as well as their societal impacts. Climate system models are based on quantitative methods and are built on a broad spectrum of measurement programs that allow examination of possible futures. Physical models that combine processes and interactions of the atmosphere, oceans, land surface, and ice easily exhaust current computational resources. Moreover, even as models advance via improved understanding, they increasingly are representing and incorporating previously unaccounted physical, chemical, and biological mechanisms. The resulting computational challenges are formidable and compounded further by the need to integrate knowledge of the physical climate with biological and anthropogenic influences such as vegetation, energy use and technology, economics, land use, hydrology, and agronomy.

The demands on this evolving predictive capability are intensifying and progressively more varied. Reliable climate information—usable by public and private decision makers—is needed on regional scales and for a variety of aspects relevant to society, including U.S. energy policy, of which the Department of Energy (DOE) is the steward. This need is a key rationale for establishing an integrated modeling program, as many scientific challenges can be addressed with similar models or with components of a comprehensive portfolio of models developed in coordination. This chapter provides a strategic foundation to motivate, organize, and support development of such a program.

5.2 Resources and Capabilities

DOE, in partnership with the National Science Foundation, has supported and released the Community Climate System Model (CCSM), Version 4. Previous versions of this model have been used to simulate 20th century climate and perform climate change projections for various national and international assessments. Version 4 will be used in similar applications. A variety of development activities continues on a suite of modeling capabilities ranging from (1) process-level models (i.e., those that quantify an isolated process such as cloud-aerosol interactions) to (2) component models (e.g., atmosphere, ocean) to (3) climate system models, which are composites of component models. DOE has supported the development of Integrated Assessment Models (IAMs) that include human activities, economics, and environmental policy.

DOE also has begun to develop Earth System Models (ESMs) that project the interactions of human activities and the physical and biological climate. A state-of-the-art analysis environment for climate modeling now exists, but description and quantification of uncertainties are at an early phase. Fundamental research supported by DOE's Office of Biological and Environmental Research (BER) is developing an Earth System Modeling capability and analysis environment. The program supports the following major capabilities:

- Physical component models that have been integrated into global and regional models. These include:
  - Ocean circulation models [Parallel Ocean Program (POP) and a Hybrid coordinate POP (HYPOP)].
  - A sea-ice model [Community Ice Code (CICE)].
  - Community Ice Sheet Model (CISM).
- Process models that have been integrated into ESMs. These include:
  - Coupled carbon- and sulfur-cycle models.
  - Atmospheric chemistry models.
  - Aerosol models (modal schemes).
  - Dynamic vegetation models.
- A coupled climate model (the CCSM 4).
- IAMs to support the determination of safe levels of greenhouse gas concentrations in the atmosphere. IAMs include representations of various determinants of greenhouse gas emissions; economic, energy, and land-use decision making; and the atmosphere, climate, oceans, and climate impacts and adaptation.
- Continued development of:
  - Nonhydrostatic and global cloud-resolving models.
  - New dynamical cores.
  - Representations of human activities in integrated ESMs.
  - Processes that facilitate the understanding of magnitudes and probabilities of abrupt climate change.
- Exploration and evaluation of regional-scale methodologies and techniques.
- Improvement of computational throughput through increased scalability and performance.
- Federated data repositories providing leading technology to facilitate the research community's access to national and international model data.
- Model diagnostics, including:
  - Advanced methods and tools for climate model diagnosis and intercomparison [e.g., Coupled Model Intercomparison Project (CMIP)].
  - Testbeds to evaluate cloud and aerosol processes.
  - Methods focused on identifying and reducing model errors.
  - Performance metrics for gauging model improvement and identifying relative strengths and weakness of models.
  - Detection and attribution analysis for understanding climate variability and change.
  - Efforts to assess climate sensitivity and natural and forced climate variability, including analysis of multimodel projections.
  - Nascent efforts to quantify the uncertainties and feedbacks in Earth system processes.

5.3 Desired Outcome

ESMs integrate our research-based knowledge of human activities and the climate and are essential tools to quantify the interplay between energy use and climate. Over the next decade:

BER will develop and test an application-focused comprehensive Earth System Modeling capability and analysis environment, which includes natural and human Earth systems, information on climate change at decade to century time scales and local to global spatial scales, and descriptions and quantification of uncertainties.

Developing an ESM that can be used for projecting future climate change is a continuous series of steps in which new processes and methods are added and tested. This suggests cyclic model development in which the application of a model from one development cycle serves to identify the strengths and weaknesses that describe uncertainties to be addressed in the next model released in the cycle. The 5-year interval between Intergovernmental Panel on Climate Change (IPCC) assessments and the approximately 2- to 3-year cycle for model development provide typical time scales for the release of new model code. Regular releases of model cycles assure integration, testing, and evaluation of modeling capabilities to be used to meet DOE Office of Science needs, including participation in the federal climate-science community and in national and international assessments.

Development cycles will take place through campaigns focused on answering science questions. Two ultimate scientific goals are to understand and quantify the coupled Earth system. Hence, scientifically investigating the coupling of processes also is a focus. Since other objectives are describing and quantifying uncertainty, the applications need to address a set of issues whose uncertainty is discerned as important. Within this context, we endorse the following as appropriate examples of ambitious, important, and integrative application areas:

- Determine the sign of the carbon cycle feedback and how it changes over time.
- Identify the impacts of warming in the Arctic and the global implications of Arctic change.
- Quantify the rate and magnitude of sea-level rise.
- Quantify the rate and magnitude of global climate response to land-use change, including impacts of deploying new energy systems.

To manage the complexity of developing this modeling capability, we propose a strategy organized under four broad, interrelated themes and goals. These themes address implementation, process, analysis and evaluation, and uncertainty—all essential elements of the program.

1. **Developing a Comprehensive and Integrated Earth System Model.** A comprehensive and integrated ESM includes physical components (e.g., atmosphere, ocean, land surface, sea ice, and ice sheets), biogeochemical components (e.g., atmospheric chemistry; land and ocean biogeochemistry; and carbon, nitrogen, sulfur, and other cycles), and IAMs of human decisions (e.g., energy use and emissions, land-use and land-cover change, economics, and policy decisions). Such a model also captures a variety of space and time scales, each represented by submodels that describe the behavior of observed phenomena. The comprehensive and integrated ESM will incorporate resolved dynamics, parameterizations of unresolved physical and biological processes, and algorithms to couple submodels and component models. Further progress requires:
    - Incorporating and improving processes in global models, including missing physical components (e.g., ice sheets) and dynamic vegetation, new biogeochemical components, and improvements in process representations needed to reduce model bias.
    - Adding the effects of human decisions by coupling IAMs with an ESM.
    - Performing and using ESMs at the highest level possible on current and future computer architectures.
2. **Developing a Comprehensive, Multiscale Modeling Capability.** One of the defining characteristics of the climate system is the strong interactions across time and space scales that occur within and between physical and biochemical components. Many dominant modes of variability in the climate system (e.g., El Niño–Southern Oscillation) exist through interactions across broad spatial and temporal scales. The most relevant aspects of global climate change

(such as shifts in temperature, precipitation, and sea level) emerge through the rectification of processes occurring at spatial and temporal scales well beyond current modeling capabilities. Modeling research often advances by focusing on quantitatively describing the processes that make up these interactions. Robust, comprehensive, and integrated models require explicit attention to the physics of coupling between spatial and temporal scales—that is, between submodels and component models. Building a comprehensive, multiscale modeling capability requires:

- Developing new algorithms and methods for capturing multiple spatial and temporal scales within a single model simulation. This includes investigating varying equation sets at different spatial and temporal scales.
- Emphasizing the construction of multiscale physical parameterizations in each physical system component and the ways these parameterizations interact within and between system components to produce dominant features of the observed climate system.
- Developing the ability to capture spatial and temporal scales—along with associated physical processes—at different resolutions in different parts of the global domain, especially related to the simulation of regional climate.

3. **Establishing Applications and Frameworks for Model Evaluation.** Applying projections from integrated ESMs to scientific investigations and decision making is, ultimately, of primary interest. Scientific rigor requires full evaluation of the quality of projections by independent researchers. Formally, this is the validation step of the scientific method and requires the participation of scientists who are expert in observations and their quality. A dedicated group of scientists familiar with the applications of models and quantitative assessment of their strengths and weaknesses is needed. Fully evaluating simulation results for impacts assessment requires developing and maintaining flexible and customizable analysis tools and the computational environment to implement them. DOE has been responsible for distributing all such assessment results for IPCC's Fourth Assessment Report (AR4) and will continue to do so for AR5. With the increasing model complexity, growing diversity of simulation types, and use of information from several modeling centers, the logistics, methods, and complexity of full model evaluation are expanding. An extensive simulation, analysis, and distribution effort requires:

   - Participating in national and international assessments of climate change and its impacts.
   - Developing advanced tools for distributing and visualizing data and for performing detailed analyses.
   - Developing and deploying information technology–based environments, performance metrics, and diagnostics for model validation and intercomparison and using these tools to describe and analyze uncertainties of climate change projections.

4. **Describing and Quantifying Uncertainty.** Uncertainty of the knowledge produced from climate change projections is an essential product of scientific investigation. Addressing uncertainty is both explicit and implicit in determining priorities in the development path of BER's integrated ESM capability. Uncertainty must be described and communicated in a form meaningful to scientists and usable by public and private decision makers. This presents a fundamental challenge to climate modeling scientists and programs because the use of uncertainty spans many disciplines. Simply striving to reduce uncertainty is not necessarily the primary hurdle in assuring the usability of uncertainty estimates. More tractable and potentially useful objectives are describing sources and types of uncertainty; analyzing the interaction of these sources and types; and, when possible, quantifying uncertainty. A particular focus is identifying high-risk, low-probability events. The following list organizes uncertainties by type and serves to motivate development paths for a modeling program.

   - Quantifying primary variable uncertainty (e.g., temperature) and integrated responses (e.g., sea-level rise) and presenting this information in a way suitable for risk analysis.

- Addressing uncertainty related to biases and misrepresentation of the variability of multi-scale, coupled processes and phenomena in climate models (e.g., mean state tropical biases and sea ice).
- Addressing uncertainty related to mechanisms and processes known to be missing from climate models (e.g., ice sheet models and groundwater flow).
- Exploring uncertainty related to specification of emission scenarios and, more generally, human enterprise.

Developing a Comprehensive and Integrated Earth System Model

The development of an ESM that can be used for projections of future climate change is a continuous process by which new processes and methods are added and tested. Here we identify goals for developing new methodologies to improve and create new models over the next decade.

Near-Term Goals (1–3 years)

- Incorporate new component and process models. In this time frame, several new models under development will require implementation and evaluation, including those for dynamic vegetation, ice sheets, indirect aerosol effects, and the carbon and sulfur cycle (with methane). Improvements in all other component models—such as new atmospheric dynamical cores—will continue, as will incorporation of better process representations in all components. In addition, one or two persistent and outstanding model biases should be chosen for focused reduction. All these improvements will form the basis of next-generation models for assessment activities beyond IPCC AR5.
- Continue current efforts toward the first generation of integrated ESMs. This project is centered on coupling climate and ESMs with IAMs and is based on the CCSM, Community Land Model, and Global Change Assessment Model. This effort initially will be focused on changes in land use and land cover; associated carbon feedbacks, water use, and hydrology; and biofuels.
- Deploy new computer architectures with multicore and hybrid processors. A concerted effort on model algorithms, programming models, and code design will be needed to adapt to these new architectures. Such a focused effort, similar to the transition in the early 1990s, will require collaborations with the DOE Office of Advanced Scientific Computing Research.

Mid-Term Goals (4–7 years)

- Incorporate new component and process models. As in the near-term, new models under development will require implementation and evaluation during this time frame. New ocean and ice components and atmospheric dynamical cores are scheduled to be completed in this period. Surface and subsurface hydrology models are likely to be important additions also. Model biases identified in IPCC AR5 will provide targets for additional process improvements. Further chemical and biogeochemical enhancements will be ready too. These will form the basis of the next two generations of models for any assessment activities beyond IPCC AR5.
- Begin to implement and optimize advanced time integration techniques into ESMs. Further exploration of initial state issues for decadal prediction with convergence on appropriate methodologies will continue.
- Conduct initial simulations and evaluations of first-generation integrated ESMs. Development of next-generation integrated ESMs will begin, coupling more processes and identifying important feedbacks.
- Deploy new computer architectures. Some convergence and decisions on programming models likely will occur during this period, and detailed performance analysis will lead to further performance tuning.

Long-Term Goals (8–10 years)

- Begin to integrate ESMs, integrated ESMs, regional modeling, and other improvements into our goal: the comprehensive and integrated ESM. Such an integration should start to be possible during this time and likely will extend beyond 10 years.

- Begin initial grand challenge simulations of cloud-resolving models for short time integrations.
- Continue required physical and computational improvements. These will be determined by analyses of model performance.

Developing a Comprehensive, Multiscale Modeling Capability

The goals outlined in this section relate to the desire of achieving higher-fidelity simulations of the coupled climate system while recognizing that models will always be under-resolved. In other words, there will always be relevant spatial and temporal scales present in the observed climate system that cannot be accommodated in our globally uniform, high-resolution grand challenge simulations.

Near-Term Goals (1–3 years)

- Increase focus on regional modeling and evaluate methodologies for regional climate models. This short-term evaluation will include global high-resolution models, variable-resolution global models, and nested regional models.
- Test and evaluate new methods for treating multiple time scales of interest in a single model. This is required because high-, nested-, and variable-resolution models introduce difficulties with time integration. Also needed is examination of appropriate initial states for short-term prediction, including predictability experiments using both model and data-assimilated initial states.
- Continue longer-term research toward models with "direct" simulation capability of clouds, ocean eddies, land ice streams, and other relevant physical processes. Along with this effort will be the exploration of scale-aware parameterizations for use within a global, multiscale modeling environment.

Mid-Term Goals (4–7 years)

- Based on near-term evaluation of regional modeling, identify appropriate approaches and integrate them into the integrated ESM framework. During this time period, simulations and evaluation will take place. Research will continue toward the "direct" regional simulation of computationally challenging physical processes (clouds, ocean eddies, and land ice streams) within a global, multiscale modeling environment.
- Develop physical and biochemical process models. These models will use different model equations and physical parameterizations as functions of local spatial and temporal resolution.
- Perform the first fully coupled climate simulations using a multiscale approach across numerous physical and biogeochemical components. This approach will allow the regional study of clouds, ocean eddies, ice streams, and other physical processes not able to be accommodated in globally uniform, high-resolution grand challenge simulations. These regional studies in turn will inform the configuration of grand challenge simulations.

Long-Term Goals (8–10 years)

- Make available integrated ESMs with multiscale capability. Issues regarding the lack of robust, scale-aware parameterizations likely will remain.

Establishing Applications and Frameworks for Model Evaluation

These goals are focused on the actual application of a model for mission needs. Participation in any national or international assessment will occur as necessary. Such assessments and related multimodel analyses will require computational infrastructure for distributing, analyzing, and visualizing model projections and output. New tools and techniques will be developed to analyze the set of campaigns focused on essential, coupled, multiscale processes. A strong concentration on uncertainty description and quantification is needed so that decision makers can assess risk and devise mitigation and adaptation strategies. Additional requirements are environments for model validation that provide both test problems and gridded observational datasets.

Near-Term Goals (1–3 years)

- Perform simulations for IPCC AR5 and create a distributed archive for the CMIP Phase 5 (CMIP-5) using Earth System Grid (ESG) tools and infrastructure. Also during this time, conduct multimodel analyses on CMIP-5 data to evaluate how realistically CCSM 4 and other current models simulate the recent past. Analyze projections of future climate change on two time scales: near term (to about 2035) and long term (to 2100 and beyond). The range of scenario experiments will permit further examination of initial state and predictability, carbon cycle feedbacks, and other factors.

- Explore causes of and solutions to persistent model biases. Despite ongoing model improvements, well-known biases continue to persist in most models. For example, tropical biases are common, as are systematic errors in fields of sea ice. Identifying the root causes for such errors has proven difficult and generally is best accomplished with a strategy that enables additional (sensitivity) experiments. Persistent errors will continue to be identified in current models (CMIP-5) and be further diagnosed in existing and new experimental testbeds.

- Begin developing the next-generation ESG. Features will include new analyses, parallel and distance visualization capabilities, and new interfaces for nonexperts to interact with climate model data.

- Identify new model metrics for regional evaluation, statistics for extreme events, integrated ESM output, and other analyses required for model improvement and needs of decision makers.

Mid-Term Goals (4–7 years)

- Perform simulations for future assessments and distribute data and multimodel analyses to the climate community. Make new projections with new model additions (e.g., ice sheets, sea-level rise, dynamic vegetation, methane) and incorporate changes identified to reduce bias in the last assessments. Projections will include sea-level rise and other quantities now available, with further explorations of decadal predictability and the impact of initial state.

- Continue exploring causes and solutions to persistent model biases. Characterize and investigate new modes of variability that arise because of introducing, for example, dynamic vegetation and ice sheet models, indirect aerosol effects, and carbon- and sulfur-cycle models (with methane).

- Deploy the next-generation ESG and continue developing future generations with increasing usability beyond the climate community.

- Complete and evaluate the regional-scale effectiveness of initial simulations of robust, ultra–high resolution models. Similarly, evaluation of other nesting and variable-resolution approaches should be complete, and initial projections using these approaches can begin. Focus regional simulations on regions of importance. Create a framework and datasets for evaluating regional projections with new regional models and ultra–high resolution global models. Also begin analyzing climate extremes in simulation data with high spatial and temporal resolution.

- Develop the tools and methods to evaluate and validate the integrated ESM. This will require not only datasets for physical models, but also data needed to validate integrated assessment components.

Long-Term Goals (8–10 years)

- Perform simulations and assessments using fully integrated ESMs that can simulate global and regional changes, incorporate human decisions, and include physical and biogeochemical processes. This integrated capability will enable DOE researchers and decision makers to examine a wide range of scientific issues, climate change scenarios, and important feedbacks.

Describing and Quantifying Uncertainty

Describing and quantifying uncertainty require documentation of the types of uncertainties being addressed. This is needed at each step of the previously identified goals that support model development, multiscale process coupling, and application analysis. An overarching consideration for uncertainty is ensuring that scientific knowledge can be better used to assist decision makers with risk assessment needs. This will require scientifically investigating uncertainty and its use. BER is uniquely positioned for this research because its programs include IAMs and social scientists.

Near-Term Goals (1–3 years)

- Test existing and emerging ensemble-based uncertainty specification methodologies for climate models. Initial experiments should be performed with component models or simplified models (e.g., atmosphere-only models or with coupling to a simplified “slab” ocean).

- Assess the utility of different methodologies and identify approaches to be actively aligned with model development and applications.
- Initiate research on how uncertainty is used by decision makers.

Mid-Term Goals (4–7 years)

- Apply selected uncertainty quantification methods to available model simulations and use these results to identify new areas for model development.
- Further develop tools for improved robustness and explore possible avenues to reduce some model biases.
- Integrate research on the use of uncertainty by decision makers with uncertainty specification of model projections.

Long-Term Goals (8–10 years)

- Distribute projections generated by the modeling capability that include uncertainty estimates, both quantitative and descriptive. Concurrently with actual model results, ESG will provide a robust and easy interface to uncertainty information for experts and nonexperts.

6. Integating Science Discussion Paper

6.1 Challenges and Expected Outcomes

The challenges of synthesis and integration for the Office of Biological and Environmental Research's (BER) overall climate change research program are somewhat different than for the program's individual components. These overall challenges are:

- Identify internal scientific links among the different elements of BER research activities on climate change.
- Identify external scientific links needed for BER's climate research activities to succeed.
- Identify gaps that need to be filled or research areas that do not take full advantage of existing capabilities.

The expected outcome of a successful synthesis and integration effort is a scientific program that is:

- Internally consistent, has appropriate links among process research activities, and supports modeling tasks in multiple disciplines.
- Appropriately linked to measurement, experimental, and modeling programs outside the Department of Energy (DOE) but nonetheless necessary for success of its climate activities.
- Supportive of and relevant to the appropriate BER program metric.
- Capable of adapting to changing circumstances and new discoveries.

Continued synthesis and integration might prove useful in many areas of the overall climate research program. For example, Earth System Models (ESMs) do not represent some important terrestrial ecological processes (e.g., disturbance) or functional processes (e.g., methane generation and consumption within soils) particularly well. Considering this, what are the appropriate lessons for experimentalists within the program? Which experiments are the most important to conduct? Which observational programs could contribute to improvements in these model representations? What existing datasets might be exploited to improve representation of these processes in ESMs?

ESMs are beginning to incorporate aspects of the energy system, land use, and climate dynamics in interactive ways, but which of these might come into play first, and why? How will the program choose new parameterizations for physical processes as models change substantially in scale and scope and as new experimental data become available? How then will models be evaluated and challenged with observational data, and how will various forms of model uncertainties be identified and begin to be quantified?

6.2 Integration and Synthesis Working Group

During the workshop, a small working group was organized to focus particularly on these challenges and on outcomes for BER's overall climate program. Members of the working group circulated among the three disciplinarily oriented breakout sessions (atmospheric science, terrestrial science, and climate modeling) and solicited the participation of the chairs and several members from each group. At the end of the first day, a discussion was held specifically on the topics of synthesis and integration, and results from it were presented in the plenary session the next morning. At the end of the second day, a final summary was prepared to reflect the overall discussion and conclusions among the integration working group members and the ensuing plenary sessions.

6.3 Goal of Climate Program Integration

The overall scientific goal of the synthesis and integration component of climate change research is to understand the behavior of the coupled Earth system, not just its individual components. Figure 6.1, below, depicts system components and their coupling, which illustrate the breadth of this goal, especially as represented in models.

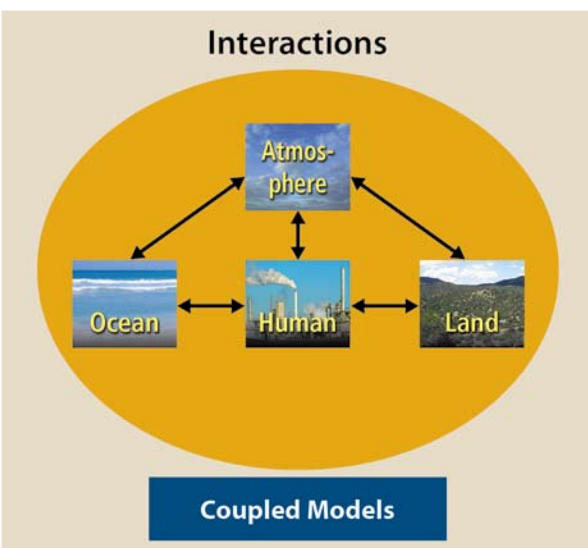


Fig. 6.1. Components and Interactions of the Earth System and Their Representation in Models.

Several implications are inherent in such a goal. Achieving it requires the explicit identification and quantification of all the various forcings on the climate system, including those that are the consequences of human decisions. These are the most rapidly changing forcings of climate and its interaction with physical, biological, and human components of the Earth system. Ignoring them thus would lead to a scientifically biased understanding of Earth system dynamics.

This goal also forces a research program to focus explicitly on the complexity of the overall coupled system, not just on that of its individual components. Increasing our understanding of these components is necessary but by no means sufficient for attaining the program's overall goal. Clearly, this requirement makes model evaluation and the identification and, ultimately, quantification of uncertainty both important and daunting.

Finally, this goal implies that the scientific problems of most interest should be those that cut across these different components of the Earth system (i.e., those that require examining more than one component to test hypotheses or answer scientific questions).

6.4 Programmatic Challenges

Although this notion of scientific integration and synthesis generally is appealing intellectually in addressing questions about the coupled Earth system, it presents several implementation challenges for the overall program. For example, how is the desire to address the coupled Earth system balanced with the necessity of increasing our understanding of individual components? How do we deal with the tension between discovery science, without regard to potential utility, and science that is both tangibly useful and intellectually interesting and challenging? What sort of program management steps might be taken to ensure balance, and how does the program avoid a problematic image of attempting to build a "model of everything"?

Pragmatically, the most productive path forward would be for the overall program to adopt a philosophy of working in "campaign" mode. This idea—which arose independently in several working groups—implies that the program should not necessarily seek to make progress on all possible problems in climate science simultaneously. Instead, it should seek to focus the community's effort on a few tractable challenges over shorter periods of time and to structure research around the delivery of "products" in manageable time frames. No single campaign need involve all research communities at once; the BER climate program certainly is large enough to support several campaigns simultaneously. To avoid jumping from issue to issue, DOE will need to periodically evaluate scientific progress and resist the temptation to continue pursuing problems simply because they have been studied historically and there is more to learn (which, after all, will always be true in science).

The program also will have to recognize that some problems are so difficult to resolve, either theoretically or empirically, their campaigns might need to be structured over longer time periods than others. The general view of workshop participants is that thinking programmatically in terms of campaigns will enable DOE to identify problems of special importance—not only to Earth science, but to the missions of DOE, its unique assets, and the experience of its research community.

6.5 Potential Examples

The synthesis and integration group discussed several scientific issues and questions that would meet the criteria described above and might serve as examples of the kinds of problems the BER climate program could address. In this section, each example is outlined without seeking to describe all possible details or competing hypotheses. Note that these are examples and do not represent a comprehensive list by any means; nor does listing them imply that they have been assigned priorities. Nevertheless, the following example questions provide a reality test of the concepts described above (i.e., that such problems in the science of the Earth system are amenable to the campaign mode of operation and are relevant to DOE missions, experience, and expertise).

Example 1: What is the Sign of the Carbon Cycle Feedback and Its Changes over Time?

Some good evidence from modeling studies suggests that the carbon cycle feedback to the physical climate system has the potential to be positive and to amplify the surface temperature response to a given amount of anthropogenic greenhouse gas emissions. The importance of testing this phenomenon is clear: if the positive feedback is large, or long-lasting, then the Earth system could be much more sensitive to a given amount of emissions than we currently understand. There is also no reason to think that the carbon cycle feedback itself is constant over time, since it depends on the reaction of many biological processes and on human decisions about emission trajectories—each of which interacts with various changes in the physical climate system.

Addressing the different facets of this problem will require greater process-level sophistication in terrestrial system models that simulate various aspects of the carbon cycle. These include demographic and disturbance processes resulting from fire and harvesting regimes (i.e., factors associated with human land use). Also needed is process-level ecophysiological understanding that can be obtained only from experimenting on and observing intact ecosystems. Coupling terrestrial and human-factor models with models of atmospheric composition and the physical climate system also will be necessary, as will understanding the enormous human perturbation of the carbon cycle and the role energy technologies play in this occurrence.

Example 2: What are the Impacts and Feedbacks Associated with Changes in Arctic Regions?

The unexpected and rapid reduction in summer sea ice in the Arctic has revealed a physical phenomenon that we clearly do not understand completely. This situation has important implications both for the ocean-ice-albedo feedbacks in the climate system and for marine and terrestrial Arctic ecosystems. The ice phenomenon raises the potential not only for changes in internal physical feedbacks in the climate system, but also for positive feedbacks from changes in Arctic biogeochemistry.

Addressing the various aspects of this problem will require significant modeling and observational studies of Arctic terrestrial and oceanic environments and of the range of couplings they exhibit with the atmosphere. Also necessary is a much better understanding of the interaction of Arctic hydrology and climate variability with the biogeochemical processes occurring in the very deep pool of biological carbon locked in permafrost and other Arctic landscapes. In its climate modeling program, DOE already has projects exploring some features of this overall issue, so clearly this presents an opportunity to use DOE's unique assets and experience.

Example 3: What are the Future Rates and Magnitudes of Sea-Level Rise?

The practical and programmatic importance of understanding future rates and magnitudes of sea-level rise is obvious. Scientifically, though, this research arena also is a source of both empirical and modeling uncertainties. These uncertainties range from the physical dynamics of ice sheet expansion and loss to the physics and mechanics of ice flow and calving into the ocean to the coupling of the fate of land glaciers and thermal expansion of the oceans. Ultimately, models of these physical processes need to be detailed enough to make some judgments about how changes in mean sea level may be linked with coastal dynamics so that model results can be localized and interpreted more broadly. Interdisciplinary studies of the consequences of sea-level rise also would be necessary—in terms of understanding both the vulnerability of the energy infrastructure (especially important from a DOE perspective) and potential adaptation measures.

This example also clearly illustrates another feature of such an interdisciplinary challenge for the BER climate program: DOE cannot be expected to pursue all aspects of this problem alone. Effectively carrying out this sort of end-to-end, interdisciplinary science will require cooperation with other agencies and entities (e.g., states and the private sector for information on vulnerability of the energy infrastructure and the National Aeronautics and Space Administration (NASA) for remote measurements of ice sheet dynamics and mean sea-level rise from satellite topographic missions).

Example 4: What are the Future Potential Rates and Magnitude of Changes in Land Cover and Use as Drivers of Global Changes?

Changes in land cover and land use currently contribute about 20% of the annual flux of anthropogenic carbon dioxide (CO_2) to the atmosphere. However, this figure is subject to substantial scientific uncertainties in terms of measurement and depends on processes that are the direct consequences of human decisions linked in part to the energy system. At the same time, changes in land cover and use are linked quite directly to the physical climate system through shifts in albedo, sensible and latent heat fluxes, and other biogeochemical and hydrologic changes—all of which together result in both regional and local consequences.

Nearly every aspect of the BER climate program involves understanding not only how today's land-use changes contribute to shifts in the physical climate system, but also what the potential future rates and magnitudes of such changes are as well as their implications for climate. These program components include flux measurements and climate, carbon cycle, and Integrated Assessment Modeling. Successfully resolving this problem would contribute to understanding the rate, magnitude, and potential changes to the apparent current terrestrial carbon sink and its interaction with terrestrial hydrology. Moreover, the fact that future terrestrial ecosystems also will respond directly to increases in atmospheric CO_2 concentrations and to climate change itself raises significant challenges for which there is no substitute for understanding the coupled Earth system.

Example 5: How Might Representation of the Hydrologic Cycle be Improved in Future Generations of Earth System Models?

An integrated and much improved representation of the hydrologic cycle in ESMs is a critical goal of the modeling community. Achieving this would enable greater regional fidelity of the models, a more accurate accounting of Earth's energy budget, and a fuller understanding of both climate impacts and their feedbacks to the climate system.

Addressing this problem requires substantial interdisciplinary interactions within the climate community. These collaborators would include, for example, atmospheric physicists interested in measuring and modeling cloud and precipitation processes; land hydrologists concerned with representing the effects of land use, topography, and soil characteristics on runoff, groundwater, soil moisture, and streamflow; and researchers focused on understanding the climate feedbacks of changes in soil moisture and irrigation.

As with the other listed challenges, improving model representation of the hydrologic cycle should involve not just DOE, but other collaborating agencies and institutions such as the U.S. Geological Survey, NASA, the National Science Foundation, and the National Oceanic and Atmospheric Administration, among others. Such complex, interdisciplinary problems demand that collaborations be sought to augment DOE resources.

6.6 Suggestions for Implementation

Discussions from the integration and synthesis group resulted in several suggestions, including the four below, for processes to implement campaigns addressing either the aforementioned questions or similar ones about the integrated Earth system.

1. Use existing advisory mechanisms within BER to help identify and prioritize an appropriate series of challenges that the climate program could seek to undertake.
2. Recognize that interdisciplinary research of the sort outlined here requires interdisciplinary funding mechanisms to succeed. This may seem obvious, but the critical point is that funding opportunities that are problem-based and cut across current program boundaries likely will be necessary. Some experience with this mode of operation already has produced several excellent interdisciplinary proposals and collaborations.
3. Realize that difficult, interdisciplinary problems are unlikely to be fully resolved in 3-year funding cycles and consider lengthening the funding cycle in some cases.
4. Recognize that such activities may be challenging, both scientifically and programmatically, but some experience already has been gained and is beginning to move in this direction. This should serve as a reminder of the potential for success.

Appendix A: Workshop Program

Climate Research Roadmap Workshop Agenda
May 13–14, 2010

Thursday, May 13

8:30 a.m.	Welcome and program goals • Bill Brinkman, Director, Office of Science • Anna Palmisano, Associate Director of Science for Biological and Environmental Research (BER)
8:45 a.m.	Workshop objectives, agenda, output (Mike Kuperberg, BER)
9:00 a.m.	Atmospheric Science (Dave Turner, University of Wisconsin)
9:30 a.m.	Terrestrial Science (Peter Thornton, Oak Ridge National Laboratory)
10:00 a.m.	Break
10:30 a.m.	Modeling (Ricky Rood, University of Michigan)
11:00 a.m.	Integration (Tony Janetos, Pacific Northwest National Laboratory)
11:15 a.m.	Charge to breakout groups (Mike Kuperberg)
11:30 a.m.	Breakouts
12:30 p.m.	Lunch provided
1:30 p.m.	Breakouts continue
3:30 p.m.	Reconvene in plenary—Report from breakouts
4:30 p.m.	Convene writing group to summarize breakout results
5:00 p.m.	Integration group meets

Friday, May 14

8:00 a.m.	Integration of climate research (Tony Janetos)
8:30 a.m.	Latitudinal challenges and needs (Jerry Melillo, Marine Biological Laboratory)
9:00 a.m.	Breakouts—Roadmap for climate research needs in: • High latitudes (Phil Jones, Los Alamos National Laboratory) • Mid latitudes (Rob Wood, University of Washington) • Low latitudes (Steve Oberbauer, Florida International University)
12:00 p.m.	Lunch provided
12:30 p.m.	Reconvene in plenary session—Reports from breakouts
1:30 p.m.	Presentation from Integration group and final comments
2:00 p.m.	Adjourn
2:00 – 5:00 p.m.	Steering committee and writing team to remain and draft summary

Appendix B: Workshop Participants and Observers

Participants

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Appendix C: BER Climate Websites

BER Climate Programs

Atmospheric System Research
www.sc.doe.gov/ober/CESD/asr.html

Atmospheric Radiation Measurement Climate Research Facility
www.sc.doe.gov/ober/CESD/acrf.html

Terrestrial Ecosystem Science
www.sc.doe.gov/ober/CESD/ter.html

Regional and Global Climate Modeling
www.science.doe.gov/ober/CESD/regional.html

Earth System Modeling
www.science.doe.gov/ober/CESD/esm.html

Integrated Assessment Modeling
www.science.doe.gov/ober/CESD/ia.html

Climate Models and Tools Referenced in This Report

Program for Climate Model Development and Intercomparison
www-pcmdi.llnl.gov

Parallel Ocean Program
climate.lanl.gov/Models/POP/

Community Ice Code
climate.lanl.gov/Models/CICE/

Community Land Model
www.cgd.ucar.edu/tss/clm/

BER Climate Reports and Plans

DOE Climate Change Research Program: Strategic Plan (2008)
www.sc.doe.gov/ober/Climate%20Strategic%20Plan.pdf

BER Atmospheric System Research Science and Program Plan (January 2010)
www.sc.doe.gov/ober/Atmospheric%20System%20Research%20Science%20Plan.pdf

Scientific Grand Challenges: Challenges in Climate Change Science and the Role of Computing at the Extreme Scale (November 2008)
www.sc.doe.gov/ober/ClimateReport.pdf

Science Challenges and Future Directions: Climate Change Integrated Assessment Research (June 2009)
www.sc.doe.gov/ober/IA%20Workshop_06-25-09.pdf

Carbon Cycling and Biosequestration: Integrating Biology and Climate Through Systems Science (March 2008)
genomicscience.energy.gov/carboncycle/

Acronyms

ARM Atmospheric Radiation Measurement program

AR5 Fifth Assessment Report of the IPCC

ASR Atmospheric System Research

BER DOE Office of Biological and Environmental Research

CCN cloud condensation nuclei

CCSM Community Climate System Model

CERES Clouds and the Earth's Radiant Energy System

CICE Community Ice Code Model

CISM Community Ice Sheet Model

CLM Community Land Model

CMIP Coupled Model Intercomparison Project

CMIP-5 Coupled Model Intercomparison Project Phase 5

CRM cloud-resolving model

DOE U.S. Department of Energy

ESG Earth System Grid

ESM Earth System Model

ENSO El Niño–La Niña-Southern Oscillation

GCM general circulation model

GCSS GEWEX Cloud System Study

GEWEX Global Energy and Water Cycle Experiment

HYPOP Hybrid coordinate Parallel Ocean Program

IAM Integrated Assessment Model

IN ice nuclei

IPCC Intergovernmental Panel on Climate Change

ITCZ Inter Tropical Convergence Zone

IWG Interagency Working Group

LES large eddy simulation

MJO Madden-Julian Oscillation

NASA National Aeronautics and Space Administration

NOAA National Oceanic and Atmospheric Administration

NSF National Science Foundation

PCMDI Program for Climate Model Development and Intercomparison

POP Parallel Ocean Program model

TOA top-of-atmosphere

USGCRP U.S. Global Change Research Program

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