DOE Climate Change Research Program: Strategic Plan

Mission: ***Advance the forefront of climate change research to provide the nation with the scientific knowledge it needs about the effects of greenhouse gas emissions on Earth's climate and biosphere to support effective energy and environmental decision making***

The Energy-Climate Issue

Today there is a strong scientific consensus that Earth's climate is changing and that the main causes of global temperature changes in recent decades are anthropogenic. In particular, the consensus is that increasing concentrations of heat-trapping (or "greenhouse") gases in the atmosphere are the chief cause of recent global warming and accelerated sea level rise, and that the carbon dioxide (CO_2) emitted from combustion of fossil fuels is the most important source of growing greenhouse gas concentrations.

The strong link between climate change and greenhouse gas emissions from fossil fuel use makes improving the scientific understanding of ongoing climatic change a priority for the U.S. Department of Energy (DOE) because the Department:

- is responsible for developing and sustaining a national energy system that is secure and environmentally sound,
- provides critical R&D to deliver future energy systems and infrastructure, which will be strongly affected by the future climate, and
- has the unique research capabilities and facilities as well as the scientific leadership needed to tackle the complex climate change science issues.

The Office of Science/Office of Biological and Environmental Research

The Office of Biological and Environmental Research (BER) in the DOE Office of Science has a distinguished history of research on climate change and on the fate and ecological consequences of CO_2 emitted during energy production from fossil fuels. It has been a key member of the multiagency U.S. Global Change Research Program (USGCRP) since that program's creation nearly two decades ago. Today it is an international leader in (1) climate-relevant atmospheric-process research and modeling, including clouds, aerosols, and the terrestrial carbon cycle; (2) large-scale climate change modeling; (3) experimental research on the effects of climate change on ecosystems; and (4) integrated analysis of climate change from the causes through to the impacts, including impacts on energy production and use and other human systems. The Department's world-leading scientific expertise and experience, its unmatched facilities for research in physics and biology, its leadership-class computational systems, and its decades-long history of leading-edge climate change research and analysis of complex systems, provide a unique foundation for DOE to lead future advances in climate change research.

The two high-priority questions that focus the BER Climate Change Research Program (CCRP) are:

1. *When, where, and by how much will climate be affected by increasing greenhouse gas concentrations in the atmosphere?*
2. *What are the likely consequences of climate change for ecosystems, the energy system, and other important human and natural systems?*

In answering these questions, BER-supported climate change research is generating the scientific knowledgebase needed to: (1) inform the public discussion about climate change, (2) support scientific considerations of energy policy options related to climate change, and (3) provide the scientific foundations and tools that can be used by the nation to plan for, adapt to, and mitigate climate change.

Strategic Focus Areas

The CCRP has five interconnected **Strategic Focus Areas**:

Focus Area 1: Climate Change Process Research
Focus Area 2: Climate Change Modeling
Focus Area 3: Climate Change Ecological Effects Research
Focus Area 4: Carbon Sequestration Research
Focus Area 5: Education

Focus Area 1, Climate Change Process Research:

- The *Atmospheric Radiation Measurement Climate Research Facility* (ACRF). ACRF is a multi-platform national scientific user facility, with platforms and instruments at fixed and varying locations around the globe for obtaining continuous field measurements of climate data to promote the advancement of atmospheric process understanding and climate models through precise observations of atmospheric phenomena.
- The *Atmospheric Radiation Measurement* (ARM) science program. The ARM science program uses data collected by the ACRF and other sources to understand interactions among water vapor, clouds, and radiation transport in order to improve the representation of these processes in climate models.
- The *Atmospheric Science Program* (ASP). The ASP employs laboratory and field studies to develop a comprehensive understanding, and model representation, of the role of aerosols in climate change, including both direct and indirect effects of aerosols on radiation transport in the atmosphere.
- The *Terrestrial Carbon Processes* (TCP) program. TCP uses both field experiments and mechanistic modeling to provide the scientific underpinnings for quantitatively projecting carbon cycle feedbacks to climate change.

Focus Area 2, Climate Change Modeling:

- The *Climate Change Prediction Program* (CCPP). CCPP seeks to improve climate change projections by developing, testing, and improving state-of-the-science climate models. These models focus on temporal scales from decades to centuries and on spatial scales from the regional to the global.

- The *Integrated Assessment Research Program* (IARP). IARP provides scientific insights into options for mitigation of and adaptation to climate change through multi-scale models of the entire climate system, including human processes responsible for greenhouse gas emissions and impacts on the energy system.

Focus Area 3, Climate Change Ecological Effects Research:

- The *Program for Ecosystem Research* (PER). PER uses unique, large-scale, long-term field experiments to discover how climate change can affect terrestrial ecosystems and the plants and animals that they sustain.

Focus Area 4, Carbon Sequestration Research:

- The *Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems* (CSiTE). CSiTE conducts basic research to understand chemical, biological, and ecological processes that might be managed in order to slow the increase in greenhouse gas concentrations by enhancing carbon sequestration in terrestrial ecosystems.

Focus Area 5, Education:

- The *Global Change Education Program* (GCEP). GCEP supports undergraduate and graduate students conducting research on climate change using mentors from the DOE National Laboratories and other institutions.

A key to CCRP's strategy and success is the program's ongoing commitment to integration among the five Strategic Focus Areas, in an effort to accelerate a systems-level understanding of climate change causes and consequences. In the CCRP program, theory, observation, experiment, and computer modeling are tightly interlinked. Basic observational and experimental research on atmospheric processes related to clouds and aerosols and on the terrestrial carbon cycle provides the data and analysis needed to develop, test, and improve climate models. The results are improved projections of climate change. The improved climate change projections are in turn used to design and interpret experimental studies of effects of climate change on ecosystems, and to assess potential effects of climate change on the energy system, such as through integrated assessments. Finally, research on the terrestrial carbon cycle is combined with carbon sequestration research and integrated assessment modeling to understand climate change mitigation options.

Outcome

In the coming decade, CCRP will play a leading role in providing the Nation's decision makers—including the public—with the scientific information they need to understand, plan for, and potentially adapt to and mitigate the environmental and economic consequences of climate change. It will produce the scientific knowledge needed to evaluate alternative energy strategies and supply the insights needed to plan new energy technologies and infrastructures necessary to meet society's demands for reliable energy in a changing climate.

Focus Area 1: Climate Change Process Research

Resolving the most critical uncertainties underlying projections of climate change

Current Situation

Projections of future climate change—which are the basis of national and international policies concerning greenhouse gas emission reductions—are limited by uncertainties in the representation of key physical, chemical, and biological processes in climate models. The three quantitatively most important uncertainties about climate change projections are (1) feedbacks to global warming from changes in clouds, (2) effects of aerosol emissions on the atmospheric radiation balance, and (3) feedbacks to global warming from changes in the carbon balance of the terrestrial biosphere. Research must focus on these processes, and the understanding to be gained from that research must be quickly and effectively incorporated into climate models.

The three *high-priority science questions* that summarize this critically needed research are:

- *What are the present deficiencies in cloud formulations and cloud feedback representations in climate models, and how can they be eliminated?*
- *What are the climatically relevant chemical and physical properties of aerosols that control their effects on the atmosphere's radiation balance, and how can they be best represented in climate models?*
- *What are the present deficiencies in terrestrial carbon cycle feedback representations in climate models, and how can they be eliminated?*

Clouds in the Climate System and Climate Change

Clouds are major agents in Earth's radiation balance. They reflect about 15% of incoming solar (shortwave) radiation and absorb a comparable fraction of outgoing terrestrial (longwave) radiation. Because a warming climate will probably change the spatial and temporal distributions of clouds, the effects of clouds on climate will probably change in the future. The magnitude of those changes is uncertain, however, and could result in a *positive* or a *negative* feedback to warming. In fact, *the largest contributor to the substantial discrepancies among climate models in their responses to changes in atmospheric greenhouse gas concentration is due to the differing ways that various models represent cloud feedbacks*—that is, changes in the way clouds absorb or reflect radiation in a changing climate. It is therefore imperative that the treatment of clouds in climate models be quickly improved.

There are many types of clouds (e.g., ice, liquid, and mixed-phase clouds) and the scientific understanding of the effects of different cloud types on climate is limited. A lack of high-quality, long-term data describing effects of clouds on the atmosphere's radiation balance has historically hampered advances in modeling those effects. Further, since climate models use coarse grids, most of the different types of clouds are not specifically "resolved" in climate models; instead, climate models use parameterizations to represent cloud effects, and it is probable that most current cloud formulations are unsuitable for use in high-resolution climate models. Another bottleneck in representing clouds in climate models is the use of one-dimensional (1-D) sub-models of three-dimensional (3-D) cloud-radiation interactions. While some 3-D formulations are used in climate models, the lack of comprehensive 3-D measurements to evaluate and improve those formulations is hindering progress.

Aerosols in the Climate System and Climate Change

Aerosols influence climate by absorbing and scattering solar and terrestrial radiation (*direct* aerosol effect) and by modifying the formation and properties of clouds (*indirect* aerosol effect). The global average net effect of present-day aerosols is understood to be a cooling that offsets a substantial portion of the warming that would otherwise occur as a result of presently elevated atmospheric greenhouse gas concentrations, but the magnitude of this offset is uncertain. Indeed, *uncertainty in aerosol-caused perturbations to Earth's present radiation balance exceeds that of all other climate change forcing mechanisms combined. This uncertainty significantly limits the ability to project future climate change and to make informed decisions about candidate energy production or greenhouse gas mitigation strategies that would affect aerosol emissions or properties.*

The spatial and temporal distribution of aerosols, their chemical composition, and their physical attributes (e.g., their optical properties and their role as cloud condensation nuclei) all affect climate. The challenge for properly accounting for aerosols in climate models is to develop simplified representations of complex mixtures of aerosols that are computationally feasible, yet still capture the effects important to climate change. High-priority research needs are improved experimental studies and theoretical interpretations of major aerosol processes, targeted field measurement campaigns in locations having important aerosol types and processes, and development and testing of aerosol process modules suitable for use in climate models.

The Carbon Balance of Terrestrial Ecosystems and its Role in Climate Change

A significant fraction of the CO_2 released to the atmosphere during fossil fuel combustion is taken up by terrestrial ecosystems (i.e., the terrestrial biosphere). As a result, the increase in atmospheric CO_2 concentration is less than it would be if all the emitted CO_2 remained in the atmosphere. It is well established that increasing atmospheric CO_2 concentration stimulates plant growth and carbon storage in terrestrial ecosystems, but the response may saturate before the end of the century. Climate change, particularly warming, has the potential to reduce the uptake of CO_2 by the terrestrial biosphere, but the timing and magnitude of such a change remain a mystery. Indeed, some coupled carbon cycle-climate models indicate a large *positive* terrestrial carbon cycle feedback to warming in the coming decades while other such models indicate a *negative* feedback. *The significant sensitivity of climate models to a terrestrial carbon cycle feedback, and the uncertain sign of that feedback, make resolving the effects of climatic change on the carbon (both CO_2 and CH_4) balance of the terrestrial biosphere a high priority.*

The critical research need going forward is to obtain a mechanistic, quantitative understanding of effects of increasing atmospheric CO_2 concentration *in combination with climate change* on the carbon balance of terrestrial ecosystems at the regional to global scales. This understanding must then be incorporated into climate models in order to accurately project future climate change.

Resources

The Department has developed the leading edge resources (i.e., research programs, facilities, and capabilities) needed to address specifically the three most important uncertainties in climate model process representations described above. Namely: (1) the joint ARM/ASP is the only climate research program that seeks a holistic view of clouds, aerosols, and the atmosphere's radiation balance, including their interactions across a range of spatial and temporal scales; (2) ACRF provides unparalleled continuous, long-term observations needed to develop and test understanding of the central role of clouds in Earth's climate and the potential for positive or negative cloud feedbacks to climate change; and (3) TCP has a long record of pioneering the design and implementation of field experiments to quantify effects of atmospheric CO_2 concentration and climate on the exchange of CO_2 between the atmosphere and terrestrial ecosystems.

The Atmospheric Radiation Measurement (ARM) science program and the Atmospheric Science Program (ASP)

The joint ARM/ASP uses coordinated and complementary approaches to quantify the effects of clouds and aerosols on the atmosphere's radiation balance. The joint program uses atmospheric measurements to explore the science of radiation transport processes, clouds, and aerosols in order to increase the fidelity of process representations (and interactions among processes) in climate models. By doing this, it provides needed inputs to the development of the next-generation of climate models, both in the United States and internationally.

The ARM science program leads the advance in treatments of clouds and radiation transfer processes in climate models. It makes extensive use of the ACRF's continuous ground-based observations through a combination of data analysis, modeling of local and regional physics, and development of parameterizations for climate models. It focuses on (1) accurate formulations for both longwave and shortwave radiation transfer calculations for cloudy atmospheres and (2) determination of how knowledge of the large-scale properties of the atmosphere can be used to explicitly simulate the micro-physical and macro-physical properties of clouds within a column of the atmosphere.

The ASP is the only federal research program with a mission to quantify the effects of aerosols on the atmosphere's radiation balance. It uses laboratory studies of the climate-relevant properties of different aerosols, field campaigns to quantify aerosol properties and atmospheric processes in their real-world setting and to test the accuracy of models of aerosols, and theoretical modeling to develop sub-models of aerosols for use in climate models. It focuses on (1) the effects of aerosols on cloud formation and cloud properties and (2) the role of black carbon and organic aerosols in climate change.

Atmospheric Radiation Measurement Climate Research Facility (ACRF)

The Department created the ACRF, a national scientific user facility, to provide critical data needed by the scientific community on cloud-climate interactions. The ACRF was the first climate change field research facility to operate cutting-edge instrumentation on a long-term continuous basis. With fixed research sites in three diverse climate regimes (i.e., the southern Great Plains of the United States, the North Slope of Alaska, and the Tropical Western Pacific), an aerial vehicles program (AVP), and two mobile ground facilities, the ACRF provides the world's most comprehensive 24/7 observational capabilities for obtaining atmospheric data specifically for climate change research. Each ACRF site uses a leading edge array of cloud- and aerosol-observing instruments to record long-term continuous atmospheric and surface properties that affect cloud formation and radiation transport through the atmosphere. The ARCF also provides shorter-term (months rather than years) measurements with its two mobile facilities (AMFs) and its AVP. This approach of combining long-term fixed-site measurements with short-term mobile measurements allows unique examination of the behavior of fundamental atmospheric processes, and the evaluation of climate model performance with respect to those processes, over a wide range of climatic and meteorological conditions.

The Southern Great Plains site, with 31 facilities in Oklahoma and Kansas, is the largest and most extensive climate research field site in the world. It was chosen for its relatively homogeneous geography, easy accessibility, wide variability of cloud types and land surface properties, and large seasonal variation in temperature and humidity. The North Slope of Alaska site, with an instrumented facility at Barrow and another at Atqasuk, observes cloud and radiation transport processes at high latitudes. The Tropical Western Pacific site (with instrumented facilities at Manus Island; Nauru Island; and Darwin, Australia) was chosen for its warm sea temperatures, frequent deep atmospheric convection, high precipitation rates, strong coupling between atmosphere and ocean, and climate variability associated with El Niño. This tropical region plays a big role in the observed interannual variability of the global climate system.

Even though the three fixed ACRF sites have been tremendously successful in producing critical cloud-radiation-climate data, some essential remaining questions (e.g., concerning deep convection and the marine boundary layer) cannot be answered without new long-term fixed sites and the implementation of next-generation instrumentation. Candidate locations for new fixed sites must be evaluated for their ability to fill important data gaps, and include the Azores (low clouds over the subtropical ocean), Greenland (site of a huge rapidly melting ice sheet), south Asia (large interannual variation in the Indian monsoon), Amazon Basin (tropical deep convective clouds), and Southern Ocean (mid-latitude storm track). New long-term measurement capabilities are needed to provide detailed analyses of the 3-D structure of cloud microphysical properties to move the treatment of clouds in climate models from simpler 1-D parameterizations to more powerful 3-D process representations. The ACRF will therefore develop an observing capability with sufficient horizontal scale to characterize the 3-D structure of clouds and their effects on the atmosphere's radiation balance.

In addition to the needs for an additional fixed site (or sites), a new mobile facility (or facilities) is needed to accelerate climate-process research. The scientific demands for the existing mobile facilities significantly exceed their capabilities and additional mobile facilities are needed for timely deployments to regions of rapid land-use change and to regions characterized by extreme conditions.

Terrestrial Carbon Processes (TCP) program

The TCP program has a long and unique history of leading-edge research on the effects of elevated atmospheric CO_2 concentration on the exchange of CO_2 between the atmosphere and terrestrial ecosystems. It pioneered the development and implementation of the free-air CO_2 enrichment (FACE) approach to field experiments. It also led the development and deployment of continental-scale research on the contemporary CO_2 balance of important terrestrial ecosystems through the AmeriFlux network of CO_2 and water vapor flux observations.

TCP is continuing to lead in the creation of understanding of the potential for significant terrestrial carbon cycle feedbacks to climate change by: (1) designing long-term, large-scale field experiments to quantify effects of controlled manipulations of climate factors and atmospheric CO_2 concentration on the carbon balance of terrestrial ecosystems, (2) optimizing the locations of sites within the AmeriFlux network to better estimate effects of present climate variability and change on the carbon balance of the terrestrial biosphere at the continental scale; and (3) using the best available experimental data and contemporary observational data to develop an integrated terrestrial carbon model (ITCM) that mechanistically simulates climate-carbon cycle interactions.

Near-Term Goals (1-3 years)

- Begin intensive characterization of the 3-D structure of clouds through an expanded ACRF horizontal measuring capability.
- Develop a candidate set of next-generation model formulations for the climatically relevant dynamics and properties of several cloud types (e.g., shallow, deep, ice, and liquid) and begin expansion of the geographic coverage of ACRF measurements (including at least one new mobile facility) to include additional climatically important cloud types.
- Develop a candidate set of next-generation model formulations for key climatically relevant aerosol processes using existing laboratory and field campaign data.
- Characterize changes and trends in exchanges of CO_2 between the atmosphere and North American terrestrial ecosystems in relation to ongoing climate variability and change through a more optimal distribution of AmeriFlux sites.
- Initiate the next-generation field experiment (or experiments) in a high-priority terrestrial ecosystem to quantify effects of climate change, in combination with elevated atmospheric CO_2 concentration, on exchanges of CO_2 and CH_4 between the atmosphere and the ecosystem.

Mid-Term Goals (4-6 years)

- Develop and validate a set of aerosol-cloud-radiation interaction sub-models using ACRF data and results of new experiments and field campaigns in order to accurately simulate effects of clouds and aerosols on the atmosphere's radiation balance across spatial scales from sub-regional to global.
- Implement a new fixed ACRF site (or sites) to provide data needed to improve and validate the representation of important atmospheric processes in climate models, including

measurements at a site experiencing relatively rapid climate change to provide needed insight into regionally important processes that are affected significantly by ongoing climate change.

- Implement a program to (1) integrate ACRF data products at the spatial scale of climate models and (2) produce a tool kit of ACRF instrument simulators for the creation of synthetic observations from climate model output to rigorously compare models to ACRF and ASP field campaign data.
- Determine the climatological controls on the exchange of CO_2 and CH_4 between the atmosphere and representative U.S. terrestrial ecosystems using systematic results from the optimized AmeriFlux network.
- Develop and validate a coupled terrestrial carbon cycle-nitrogen cycle-climate model suitable for use in coupled carbon cycle-nitrogen cycle-climate models and capable of simulating feedbacks between climate change and the coupled terrestrial carbon and nitrogen cycles.

Long-Term Goals (7-10 years)

- Complete a set of proven aerosol-cloud-radiation-climate interaction sub-models, optimize them for rapid computer throughput, and facilitate their incorporation into next-generation climate models.
- Validate coupled carbon cycle-climate change models with (1) results of the next-generation field experiment designed to quantify effects of climate change on the exchanges of CO_2 and CH_4 between the atmosphere and terrestrial ecosystems and (2) a comprehensive synthesis of AmeriFlux data from major North American biogeographic regions.
- Implement a fully integrated and accessible database of all Departmental climate change process research results, including a portal linking the database with the ACRF archives.

Outcome

Achieving these goals will enable the discovery and quantification of the atmospheric processes that are most important to climate change, namely the role of clouds and cloud feedbacks in the climate system, the role of aerosols in modifying the atmosphere's radiation balance, and the potential for terrestrial carbon cycle feedbacks to global warming. Armed with this new science, a new set of scientifically rigorous sub-models of these processes will be formulated and incorporated into climate models, with an outcome of greatly reduced uncertainties in climate change projections.

Focus Area 2: Climate Change Modeling

Advancing the Computer Models Needed to Understand Climate Change and Its Consequences

Current Situation

Priorities for climate change research have moved beyond determining if Earth's climate is changing and if there is a human cause. The focus is now on understanding how quickly the climate is changing, where the key changes will occur, and what their impacts might be. Climate models are the best available tool for projecting likely climate changes, but they still contain some significant weaknesses. Rapid model development, testing, and optimization will be critical to providing decision makers with the timely, and accurate, information they need.

The three *high-priority science questions* that summarize the critically needed output from climate change modeling with respect to the Department's mission are:

- *What are the likely pace and magnitude of future greenhouse gas emissions and how might various energy production options and carbon sequestration technologies affect those emissions and the economy?*
- *How and when would any given future trajectory of greenhouse gas emissions affect global and regional-scale temperature, precipitation, and extreme weather events (i.e., climate change)?*
- *What would be the impacts of a given climate change on the demand and supply of energy?*

Climate Modeling Needs

Ultimately, Earth system models (ESMs)—the next-generation climate change models that incorporate biogeochemistry, atmospheric chemistry, and dynamic vegetation into coupled models of the atmosphere, ocean, sea ice, and land surface—must provide improved simulations of temperature, precipitation, and extreme weather events, all at much finer scales, to help the public understand climate change and to provide the inputs necessary for assessments of the consequences of climate change. Because many effects of climate change will be realized at the local to regional scale, it will be necessary, but not sufficient, to increase the spatial resolution of climate models and to accelerate computational throughput with a combination of software and hardware advances. It will also be necessary to markedly improve process representations in models, including atmospheric chemistry and physics, oceanic (including sea ice) physics and biogeochemistry, land surface (including land ice) physics and biogeochemistry, and the dynamics of vegetation changes (i.e., possible changes in the locations and geographic ranges of terrestrial biomes). This will require incorporation into climate models of results from the Focus Areas 1 and 3 research activities, and results from research at other agencies and internationally.

Addressing uncertainties in climate change projections will require a movement towards high resolution climate system predictions, with a blurring of the distinction between shorter-term (decadal scale) and longer-term (centennial scales) climate change projections. The shorter-term projections will require initialization of the component models (i.e., ocean, land, sea-ice, and atmosphere) so the simulations are started using the best estimates, based on observations.

Challenges exist: What are the best techniques for initialization, given imperfect as well as inadequate observations, and systematic errors in models? How are predictions to be evaluated? How can models better simulate known modes of climate variability such as El Nino-Southern Oscillation and the Pacific Decadal Oscillation? Despite these currently unresolved questions, a scientific thrust on decadal prediction is imperative, given that it will guide society as it adapts and responds to climate change. Lessons and technical capabilities from the weather prediction community will be useful in this endeavor that should ultimately result in seamless prediction across all time scales.

Integrated Assessment of Climate Change

The pace of future greenhouse gas concentration changes will in large part be determined by methods of energy production, land-use changes, effects of climate change on the biosphere's carbon balance, and implementation of carbon sequestration approaches. Integrated Assessment Models (IAMs), which take these factors into account, are the central tools in exploring possible future trajectories of changes in atmospheric composition. Furthermore, IAMs have already been used, because of computational efficiencies, as a staging platform to incorporate new process understanding into climate models.

The greatest challenge for modeling the energy, environmental, and economic security associated with climate change is to improve and expand representations of impacts and adaptations within IAMs. Properly representing impacts and adaptations will require higher resolution models and regionally specific representations of processes and data. Without such improvements, the models are strong in quantifying the costs and role of mitigation but weak in accounting for the benefits, i.e., avoided damages, of actions and in understanding key vulnerabilities. Combined representations, such as those contained in IAMs, are essential for understanding the effects of multiple environmental changes on human and natural systems as well as aggregate socioeconomics and potential adaptive behaviors. Present research priorities include improving IAM representations of (1) transformational science-driven energy technology innovations; (2) non-CO_2 greenhouse gas emissions and climate effects; (3) effects of land-use changes on the terrestrial biosphere's carbon balance; and (4) carbon management, especially carbon sequestration. Progress on these is needed to reveal key insights into infrastructure vulnerabilities, cross-sectoral/resource issues such as the energy/water nexus or competition for land use (e.g., biofuels), sustainable solutions to reducing greenhouse gas emissions, and the potential consequences to human and natural systems of extreme weather events and/or abrupt climate changes.

As society explores specific mitigation strategies and prepares to cope with and adapt to a changing climate, it will require significant improvements to IAMs and closer coupling of IAMs with climate models. IAMs are critical tools for exploring the interactions of human and natural systems in driving and responding to a changing climate. Typically, IAMs represent human systems built around a socioeconomic framework that is coupled with simplified representations of the natural system to enable decades-to-centuries analyses of potential mitigation and, to some degree, adaptation strategies. Increasingly, they will be called on to explore impacts and adaptation and are a major focus of present research efforts.

Resources

The Department carefully developed leading-edge capabilities in climate change modeling and integrated assessment modeling over the past two decades. *The centerpiece of the Department's climate change research program is the Climate Change Prediction Program* (CCPP), which is a leading international effort in climate model design and development. *The Department's integrated assessment program is widely viewed as the international benchmark.*

Climate Change Prediction Program (CCPP)

The CCPP advances climate change science and improves climate change projections using state-of-the-science coupled climate models, on time scales of decades to centuries and space scales of regional to global. The CCPP develops, tests, and applies climate models based on theoretical climate-science foundations and takes advantage of emerging high performance computing and information technologies to increase both the accuracy and the throughput of climate change projections.

The CCPP jointly supports (with NSF) development and application of the Community Climate System Model (CCSM), a community-wide climate modeling program. The DOE CCSM Consortium Project is carried out at six DOE national laboratories and the National Center for Atmospheric Research. The Climate, Ocean and Sea Ice Modeling Project (COSIM) focuses on the development and distribution of the Parallel Ocean Program (POP) ocean general circulation model and the CCSM Sea Ice Model (CICE). The CCPP Program for Climate Model Diagnosis and Intercomparison (PCMDI) evaluates the performance of present national and international climate models by independently aplpying universal diagnostic tools for evaluating model performance. PCMDI also archives and disseminates climate model simulations used for the Intergovernmental Panel on Climate Change (IPCC) assessments. The CCPP-ARM Parameterization Testbed (CAPT) at PCMDI provides climate model developers a means to evaluate new parameterization schemes for processes such as cloud physics and convection in the context of a full atmospheric general circulation model. The CAPT is a key resource to improve climate models using data from the ACRF.

Extended droughts, rapid changes in Arctic sea-ice extent and duration, and rapid increase in sea level have great societal implications. The science areas that CCPP is poised to address are articulating the thresholds, nonlinearities, and fast feedbacks in the climate system; incorporating causal mechanisms into coupled climate models; and testing the enhanced models against observational records of past abrupt climate change.

Integrated Assessment Research Program (IARP)

The IARP integrates representations of the entire global climate system, emphasizing greenhouse gas emissions and actions that would affect emissions. The results of this research provide a foundation for subsequent scientific analysis or decision making. The estimated costs of certain actions can be weighed against predicted changes in impacts. The research program also helps the climate change research community better identify priority scientific topics. IARP foci include (1) development of integrated assessments, including integrated assessment models, and

(2) support of research that fills important gaps (especially related to economics) in these models.

Near-term Goals (1-3 Years)

- Incorporate model improvements into ESMs for the most significant process uncertainties including *atmospheric chemistry and physics, land-surface and sea-ice physics, land and ocean biogeochemistry, cloud feedbacks, aerosol effects, and carbon cycle feedbacks*, including key results from CCRP's process studies (i.e., Focus Area 1).
- Develop a comprehensive plan for next-generation climate model testing (evaluation), model inter-comparison, and model diagnosis for objectively assessing strengths and limitations of climate model output.
- Develop innovative ESM-IAM model coupling processes and apply the coupled model to coupled simulations such as land-use change and dynamic vegetation.
- Take on the grand challenge for IAMs of representing *impacts and possible adaptations from climate change*, thereby including the benefits (avoided damages) dimension to the cost/benefits representations, building from critical collaborations, an initial inventory (underway), and a strategic approach to obtaining sub-component models from the IAV community.

Mid-term Goals (4-6 Years)

- Resolve critical biases inherent in current ESMs such as precipitation biases and deliver next-generation statistics of extreme events.
- Develop and incorporate the sub-models in ESMs that will improve understanding of *extreme events* as well as the potential *for abrupt climate shifts and potential significant instabilities in the climate system*.
- Provide insights into potential climate tipping points and instabilities that could result in abrupt climate change.
- Investigate dynamical downscaling techniques and associated challenges to achieving higher spatial resolution in climate change projections, and pursue the grand challenge of improving precipitation predictions from high-resolution ESMs.
- Develop high-resolution, as well as specific regional, IAMs with priority near-term emphasis on energy sector impacts and vulnerabilities under climate change.

Long-Term Goals (7-10 years)

- Provide an ESM at ultra-high resolution (e.g., km scale) capable of projecting effects of increasing greenhouse gas concentrations on regional temperature, precipitation, and extreme weather events.
- Work across CCPP and IARP to develop a high resolution modeling *framework and methodology* to enable quantitative regional analyses of greenhouse gas emissions, climate change, adaptations to climate change, and overall economics of climate change and climate change mitigation scenarios.

- Produce next-generation IAM representations of human and institutional behaviors not explained by idealized economics and develop alternative metrics for situations in which monetary metrics are not supported.
- Deliver deep scientific insights into pathways for sustainability and energy, environmental, and economic security.

Outcome

Achieving these goals will produce extensively analyzed simulations of possible future climate changes that will serve as the central input to national and international efforts to understand climate change and its impacts. It will also produce the state-of-the-science set of quantitative tools that are needed by decision makers to understand the costs and effectiveness of curtailing climate change using various alternative energy production methods and carbon sequestration technologies. The outcome will be the tools and scientific understanding necessary to assess future climate changes, the effects of climate change on energy demand and supply, and options for actions to slow climate change.

Focus Area 3: Climate Change Effects Research
Understanding the Ecological Implications of Climate Change

Current Situation

Present scientific consensus is that global warming is already affecting terrestrial ecosystems by changing (1) the geographic ranges of terrestrial plant and animal species; (2) the timing of phenological events in both plants and animals; and (3) community composition and the local abundance of some species, including a few local disappearances (extinctions). In addition, changes in precipitation amount or timing, particularly in dryland ecosystems (30% of the United States is dryland), have the potential to dramatically affect mortality or success of key species, and rising sea level threatens low-lying terrestrial ecosystems near coastlines.

Three *high-priority science questions* about ecological effects of climate change are:

- *How will climate change affect the abundance and geographic distribution of plant and animal species in U.S. terrestrial ecosystems?*
- *Will climate change cause widespread mortality of dominant plant species in U.S. dryland ecosystems?*
- *Will rising sea level, in combination with climate change, threaten the health, or even the existence, of low-lying terrestrial ecosystems near the U.S. coastline?*

Because the timing and magnitude of specific ecological effects that might be caused by future climate changes are poorly understood, and because society places a high value on ecosystems and their component organisms (i.e., the plants and animals living in ecosystems), there is an urgent need to develop an improved scientific understanding of the likely effects of climatic change on terrestrial ecosystems. The attribution of recent changes in ecosystems to climate change is based on observed correlations between changes (or spatial gradients) in the environment and changes (or spatial gradients) in ecosystems. Present correlations between climate and ecosystems do not, however, provide the requisite cause-and-effect understanding needed to forecast effects of future climate changes on terrestrial ecosystems because future climates are expected to be pushed well outside the envelope of conditions in today's world. Experiments involving controlled manipulations of climate factors, and atmospheric CO_2 concentration, are therefore needed to establish cause-and-effect relationships between climate changes and effects on ecosystems.

Resources

The Department's Program for Ecosystem Research (PER) uses unique field and laboratory manipulative experiments to elucidate the biological and ecological mechanisms that must be understood to forecast ecological effects of climate change. It concentrates its research on important U.S. ecosystems, but the knowledge gained is broadly applicable at the global scale.

PER is the leader among U.S. and international agencies in the design, construction, and operation of pioneering, long-term, manipulative field experiments addressing ecological effects of climate change. PER's expertise includes controlled manipulations of temperature, precipitation, CO_2 concentration, and O_3 concentration in a variety of natural and constructed (model) terrestrial ecosystems. When operated over multi-year periods, PER's unique experimental infrastructures provide the scientific community with tools needed to understand how climate changes might affect ecosystems. (The PER field experiments have important scientific linkages to the field experiments used by the TCP program to study effects of elevated CO_2 concentration on the carbon balance of terrestrial ecosystems.) The PER experimental program produces distinctive data about potential ecological effects of climate change that adds great value to other national and international research programs focusing on (1) long-term ecological *monitoring* and (2) ecosystem *simulation modeling*.

The PER is working toward the design, prototyping, and implementation of the innovative experimental approaches and technologies that will be needed to conduct the next-generation of controlled manipulations of temperature, precipitation, and CO_2 concentration in a range of terrestrial ecosystems, including short-statured systems as well as tall forests. The PER prioritizes terrestrial ecosystem experiments based on factors such as the value society places on specific types of ecosystem and the susceptibility of different ecosystems to climate change.

Near-Term Goals (1-3 Years)

- Design and test infrastructural prototypes for the next-generation of ecosystem-scale climate change experiments (i.e., *in situ* manipulates of temperature and precipitation in combination with elevated CO_2 concentration) applicable to a range of important terrestrial ecosystems.
- Implement next-generation field experiments that encompass a broad range of warming, altered precipitation, and elevated CO_2 concentration to identify and quantify thresholds and nonlinearities in potential effects of climate change in key U.S. terrestrial ecosystems on (1) local plant and animal extinctions and (2) geographic range shifts in plants and animals.
- Implement next-generation field experiments in U.S. dryland ecosystems to understand the potential for climate change-induced mortality in key plant species.

Mid-Term Goals (4-6 Years)

- Use available data to develop a robust ecological theory to characterize the potential for warming-caused range shifts, and associated changes in local abundance, of important plant and animal species.
- Design and implement next-generation experimental approaches to study effects of sea level rise, in combination with climate change and elevated CO_2 concentration, on the health and very existence low-lying terrestrial ecosystems near the U.S. coastline.

Long-Term Goals (7-10 Years)

- Bring the next-generation experiments to successful conclusions and disseminate the results to the scientific community and the public.

Outcome

The program will answer the question "Will climate change have unacceptable effects on important U.S. terrestrial ecosystems?" so that decision makers can decide what actions are needed to prevent, or adapt to, likely effects of climate change on terrestrial ecosystems.

Focus Area 4: Carbon Sequestration Research

Exploring the Promise of Carbon Sequestration in Terrestrial Ecosystems

Current Situation

A significant fraction of anthropogenic emission of greenhouse gases is associated with land-use change, most notably the clearing of forest and plowing of grassland for agriculture. For the period prior to 1950 about half of total cumulative anthropogenic CO_2 emissions were associated with land-use change (since then fossil fuel use has strongly dominated anthropogenic CO_2 release). If the carbon previously released to the atmosphere from land-use change could be restored to terrestrial ecosystems a significant amount of CO_2 would be removed from the atmosphere. Indeed, it may be possible to increase carbon storage in terrestrial ecosystems to amounts exceeding pre-disturbance levels. This might be facilitated by basic research directed at enhancing carbon sequestration in terrestrial ecosystems.

The *high-priority science question* summarizing the needed research is:

- *What are the fundamental physical, chemical, biological, and ecological mechanisms that could be harnessed in ecosystem management programs to purposefully enhance quantitatively important carbon sequestration in terrestrial ecosystems?*

Although specific estimates vary, there is widespread consensus that the potential for sequestering carbon in terrestrial ecosystems is large, amounting to the equivalent of many (perhaps ten) years of present anthropogenic CO_2 emissions. Understanding the ability to manage ecosystems for carbon storage, and doing so in an environmentally sound manner, will be critical to future climate change mitigation planning.

Four fundamental nonexclusive approaches could in principle be taken to purposefully enhance carbon storage in terrestrial ecosystems: (1) increase the annual rate of whole-ecosystem photosynthesis (i.e., assimilation of atmospheric CO_2 by plants), (2) increase the fraction of assimilated carbon that is partitioned into long-lived tissues (e.g., wood), (3) increase the fraction of assimilated carbon that is partitioned into recalcitrant biochemicals (e.g., lignin versus cellulose in plant cell walls), and (4) increase the physical, chemical, and biological protection of soil organic matter.

A coordinated program of research on these topics is needed. Both management approaches (e.g., supplying limiting nutrients to enhance photosynthesis or modifying tillage practices to better protect existing soil organic matter) and plant improvement (e.g., breeding plants to produce a larger fraction of recalcitrant or long-lived tissues and biochemical compounds) must be considered.

Resources

The Department developed the Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE) 10 years ago. It is a coordinated effort employing scientific expertise at several DOE National Laboratories and universities to conduct multi-scale research to acquire basic knowledge for underpinning the implementation of soil carbon sequestration in an environmentally acceptable and economically feasible manner. Research is based on the premise that identifying and understanding the basic mechanisms controlling carbon sequestration in terrestrial ecosystems is fundamental to developing approaches for enhancing carbon capture and long-term storage. The goal is to discover and characterize links among physical, chemical, biological, and ecological processes controlling long-term carbon storage at a mechanistic level to facilitate the enhancement of carbon storage in ecosystems to restore, or surpass, historic levels of carbon in ecosystems.

Presently, CSiTE is focusing on basic research concerning (1) soil carbon inputs, (2) soil structural controls on carbon recalcitrance, (3) microbial community functioning and dynamics related to soil carbon turnover, (4) humification chemistry, (5) intrasolum carbon transport, and (6) mechanistic ecosystem modeling of carbon transformations and storage in soil. The goal is to understand the coupled physical, chemical, biological, and ecological controls on soil carbon sequestration at a fundamental level. Future research is expected to accelerate these efforts and effectively integrate knowledge of component processes into whole-system understanding.

Near-Term Goals (1-3 Years)

- Investigate biophysical processes associated with soil microaggregates (i.e., small volumes of soil held together by various bonding mechanisms) and their role in soil organic matter breakdown leading to the release of CO_2.
- Evaluate the potential to use specific groups of soil micro-organisms as sentinels of soil systems either accumulating carbon or losing carbon.

Mid-Term Goal (4-6 Years)

- Develop and test new mechanistic models of soil carbon chemical transformations that have the potential for application to soil carbon storage in managed and unmanaged ecosystems.

Long-Term Goals (7-10 Years)

- Complete field research evaluating relationships between aboveground biomass productivity and belowground processes for enhancing soil carbon sequestration in ecosystems used to produce bioenergy feedstocks.
- Determine the quantitative capacity for increasing carbon storage in terrestrial ecosystems within regions and across the continent, taking into account future scenarios of climate change, increasing atmospheric CO_2 concentration, altered nitrogen deposition, and changes in land use and ecosystem disturbance.
- Incorporate CSiTE data and insights into a state-of-the-science integrated assessment model to compare the effects of soil carbon sequestration approaches with other engineered technologies for reducing net greenhouse gas emissions.

Outcome

Future CSiTE research will produce rapid discovery of the scientific knowledge base needed to quantify the potential for purposeful carbon sequestration in terrestrial ecosystems. This will be a critical component of future climate change mitigation programs and will contribute to efforts to slow the increase in atmospheric greenhouse gas concentrations.

Focus Area 5: Education

Providing human capital needed to address emerging climate change research issues

Current Situation

The Global Change Education Program (GCEP) was established by BER to promote training of the next generation of scientists needed for climate change research. GCEP's approach is to engage students in early stages of their education by exposing them to the important, and exciting, scientific problems in climate change research through mentoring by authoritative scientists. BER expects that once students are exposed to climate change research needs and opportunities many will be motivated to move into the field and contribute to the needed pipeline of bright new minds. This pipeline must both replace retiring scientists and expand the total work force in this growing high-priority scientific research area.

Resources

The GCEP has two components:

- *Summer Undergraduate Research Experience (SURE)*. SURE places college and university students, during the summer after their sophomore or junior years, at DOE National Laboratories where they work with mentors on climate change research.
- *Graduate Research Environmental Fellowships (GREF)*. GREF provides fellowships to graduate students in degree programs related to climate change and fosters their involvement in collaborations between universities and the DOE National Laboratories.

SURE Fellows each have a mentor who directs and monitors their summer research experience. Mentors are recruited from all parts of the CCRP, i.e., ARM, ASP, TCP, PER, CCPP, and IARP. From 1999 through 2008, BER awarded 117 SURE Fellowships.

GREF makes three-year appointments to support graduate students, including a stipend, tuition, and fees. GREF Fellows have two mentors: a university faculty advisor and a National Laboratory research mentor who collaboratively guide their research activities. The National Laboratory mentor provides unique expertise and/or accessibility to research facilities not available at universities. From 1999 through 2008, BER awarded 83 GREF Fellowships.

Program Goals

- Catch the imagination of students at the early stage of their undergraduate training through targeted SURE advertisements on college and university campuses.
- Effectively publicize important climate change research opportunities for graduate students.
- Actively recruit students at minority-serving colleges and universities.

Outcome

GCEP is making a significant contribution to the education of the next generation of scientists that will be needed to tackle emerging climate change science issues.

Program Linkages

Creating Synergies to Answers Scientific Questions Critical to Society

The BER CCRP collaborates with other programs inside and outside the Department to foster advances in basic research on climate change for the benefit of the nation and the world.

Linkages within BER

The CCRP's CSiTE research activities are conducted cooperatively with BER's Biological Systems Science Division research on carbon sequestration, which focuses on state-of-the-science applications of genomic and proteomic tools for advancing knowledge of biologically based carbon sequestration opportunities in terrestrial ecosystems.

Linkages within the Office of Science

Many CCRP climate modeling activities are carried out collaboratively with the Office of Advanced Scientific Computing Research (ASCR). These include efforts involving (1) joint research projects through the Office of Science's Scientific Discovery through Advanced Computing (SciDAC) program and (2) computational resources made available through the Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program at the National Energy Research Scientific Computing Center (NERSC), which is an Office of Science user facility.

Interagency linkages

The CCRP is DOE's contribution to the U.S. Climate Change Science Program (CCSP), which is the 13-agency group that integrates and coordinates federal research on climate change. The CCSP combines the U.S. Global Change Research Program (USGCRP)—*which has made the world's largest scientific investment in climate change research*—with the U.S. Climate Change Research Initiative (CCRI). BER staff actively participate in CCSP interagency working groups (co-chairing several in recent years), which coordinate interagency climate change research.

Examples for climate modeling

The CCRP recognizes that effective climate change modeling is not a single-agency challenge and uses a strategy to capitalize on the strengths and capabilities of other federal agencies—notably NSF, NOAA, and NASA—to develop the climate models and to acquire the data needed to drive those models. Key interagency collaborations are: (1) DOE and NSF are the lead co-sponsors of the national Community Climate System Model (CCSM) Project, which is the leading open-source climate model in the United States; (2) DOE and NOAA actively collaborate on climate modeling, taking advantage of DOE's leadership-class computing facilities, using both the CCSM and NOAA climate models; and (3) BER-sponsored scientists work closely with NASA scientists to jointly lead U.S. climate-data assimilation research.

International linkages

CCRP-sponsored scientists are leading participates in the Working Group for Coupled Modeling and the Working Group on Numerical Experimentation as part of the Intergovernmental Panel for Climate Change (IPCC). The CCRP's Program for Climate Model Diagnosis and Intercomparison (PCMDI) is also tightly linked to international climate change research by collecting, analyzing, and archiving climate model output contributed by climate modeling centers around the world. *This unique activity allows scientists from all nations to perform research on climate models* and formed the basis of much of the IPCC's Fourth Assessment Report published in 2007. PCMDI played the same role in previous IPCC climate change assessments. CCRP-sponsored scientists also serve as co-authors and reviewers of all IPCC assessments, and CCRP research published in the scientific literature is the basis of significant parts of most IPCC assessments.

Because of the important role of the BER CCRP within the IPCC it is noteworthy that the IPCC shared the 2007 Nobel Peace Prize, with former U.S. Vice President Albert Arnold Gore Jr., "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change".