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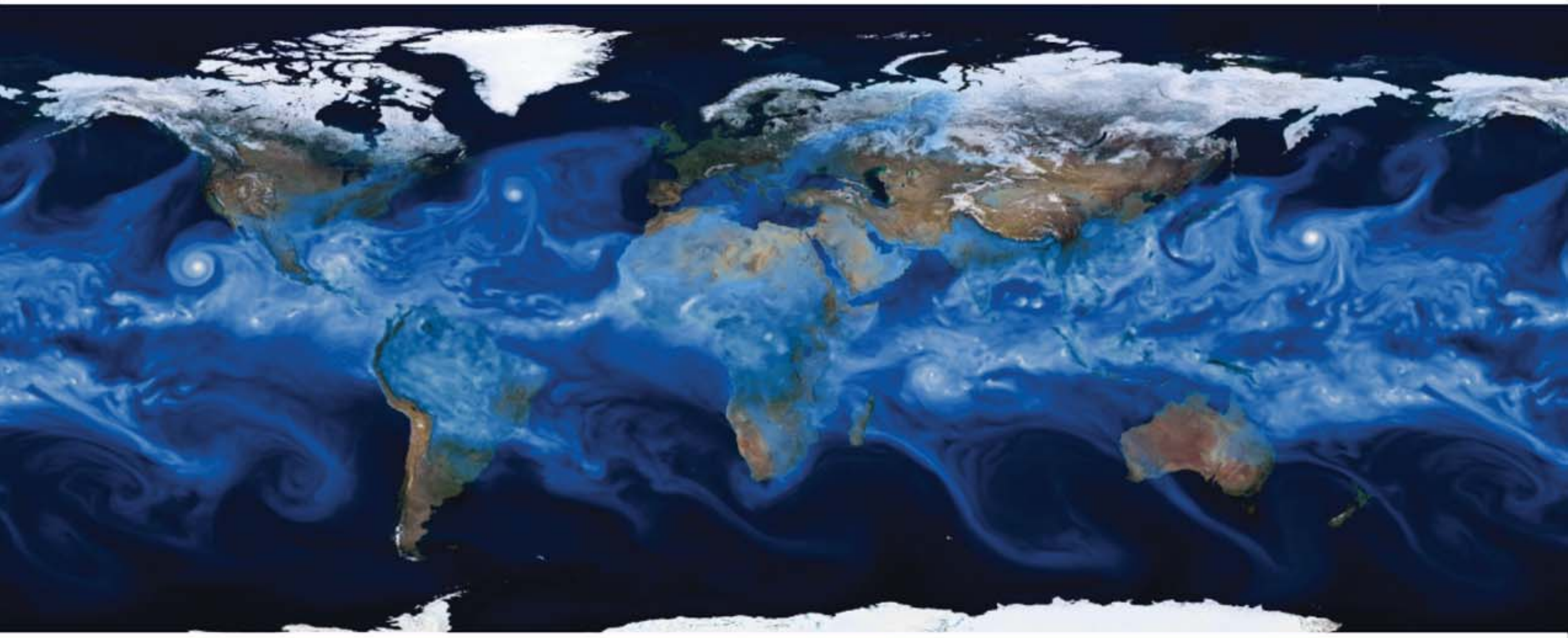

REGIONAL AND GLOBAL CLIMATE MODELING PROGRAM OVERVIEW AND STATUS REPORT

Team Leads Meeting

October 6-8, 2015

DOE/SC-0184

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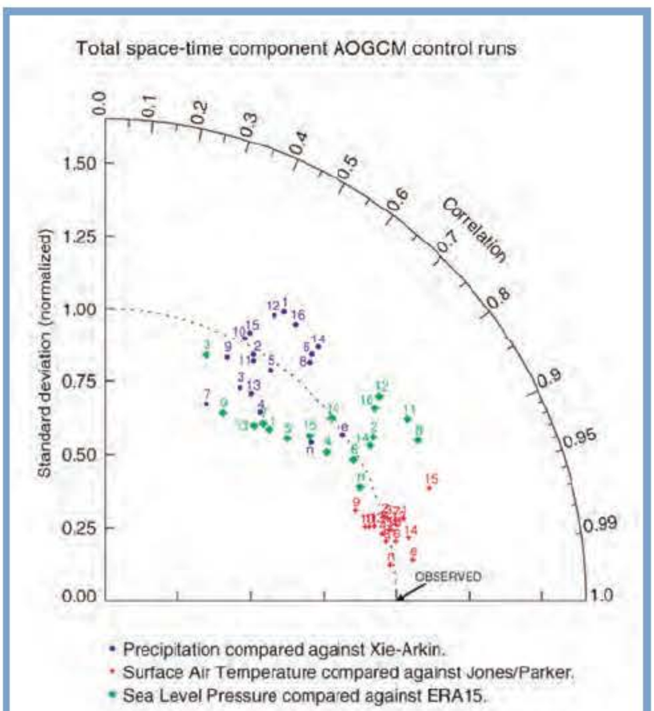
Lawrence Livermore National Laboratory: Climate Change Science Focus Area

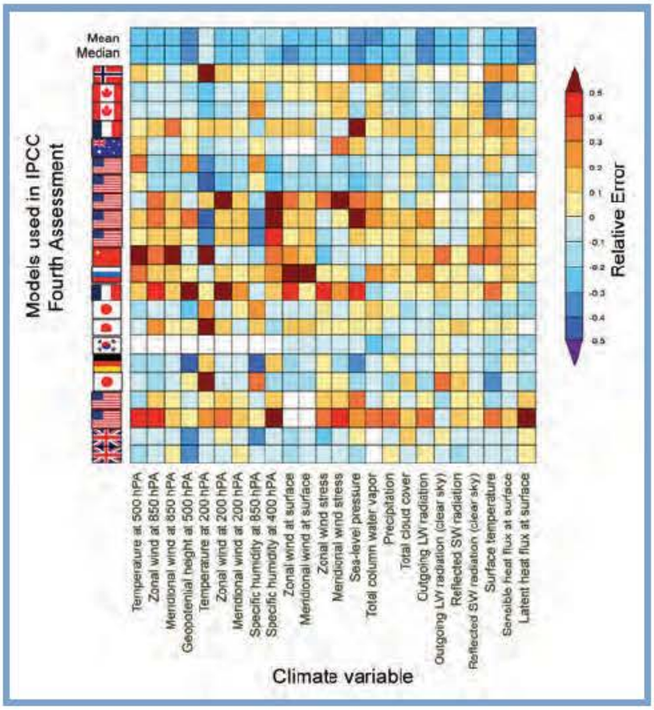
PROGRAM FOR CLIMATE MODEL DIAGNOSIS AND INTERCOMPARISON (PCMDI)

Established by the U.S. Department of Energy at Lawrence Livermore National Laboratory, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) fosters and engages in research aimed at providing a systematic and comprehensive evaluation of climate models. Working with international partners, PCMDI has inspired a fundamental cultural shift in the climate research community. Researchers now expect access to output from climate simulations, enabling widespread scrutiny and analysis.

A notable product of PCMDI's leadership of coordinated modeling activities is the Coupled Model Intercomparison Project (CMIP), which subjects models worldwide to an evolving set of standardized numerical experiments. The CMIP model output is made freely available to all researchers, leading to many hundreds of peer-reviewed publications. In addition, many of the conclusions appearing in each of the five assessment reports prepared by the Intergovernmental Panel on Climate Change are drawn from the scientific foundation of the multi-model collection of CMIP projections of future climate change.



Taylor diagrams, invented at PCMDI, are now commonly used to summarize model skill. This example appeared in the model evaluation chapter of IPCC's Third Assessment Report (2001).

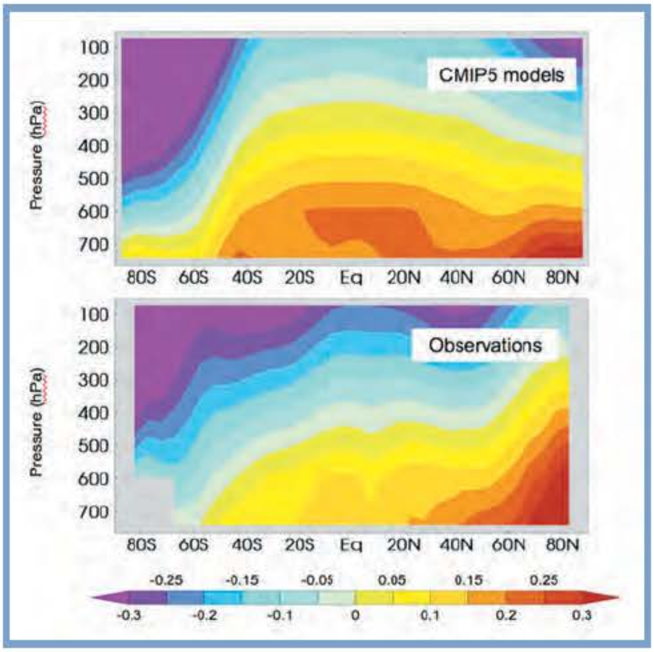


Model performance "portrait plots" show that climatological mean simulation errors are usually smaller for the statistical mean of a multi-model ensemble relative to the individual models comprising the ensemble. (Source: Gleckler et al., Journal of Geophysical Research, 2008)

RESEARCH ADVANCES

Capitalizing on the multi-model CMIP simulations that PCMDI manages, in-house research focuses on the evaluation of climate models. An overarching goal is to gauge the relative merits and limitations of individual climate models and to quantify and reduce uncertainty in model projections of climate change. PCMDI scientists have developed innovative graphical methods for displaying multiple aspects of model performance. The "Taylor diagram," for example, is now routinely used throughout climate sciences to summarize the fidelity of simulated fields. More comprehensive summaries of model performance can be presented using the PCMDI-developed "portrait plots." These plots help identify relative strengths of different models.

PCMDI is also a recognized leader of detection and attr bution (D & A)–research that seeks to identify causes of recent climate change. Work in this area at PCMDI utilizes results from the CMIP multi-model ensemble to define anthropogenic "fingerprints" of climate change that can be identified unambiguously in climate observations. Capturing results from multiple models and examining multiple aspects of climate (e.g., temperature, water vapor, ocean



"Fingerprinting" with changes in the vertical structure of atmospheric temperature: The average of eight CMIP5 models with anthropogenic forcing (upper panel) and satellite observations from Remote Sensing Systems (lower panel) both show coherent warming of the troposphere and cooling of the stratosphere. (Source: Santer et al., Proceeding of the National Academy of Sciences, submitted)

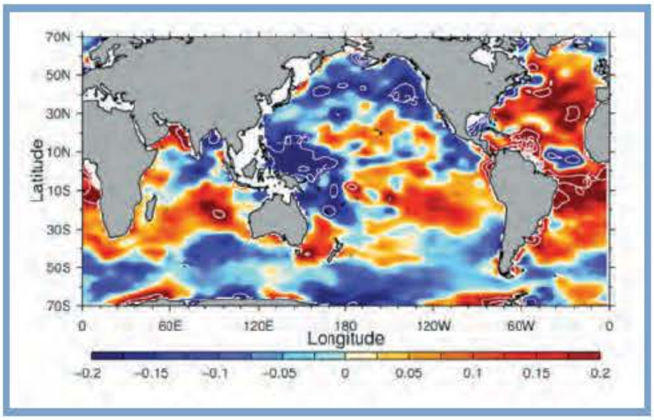
heat content, precipitation), the D & A research is uncovering the multifaceted characteristics of human-induced climate change. In line with PCMDI's overall mission, an important aspect of this research is that the models used to identify the anthropogenic climate change signal and to estimate the noise of natural variability are subjected to quality assessment tests. In the face of model differences and uncertainties, this permits sound conclusions to be reached.

Additional research at PCMDI examines the ability of models to simulate a wide range of processes and phenomena, from the variety of observed modes of atmospheric variability (e.g., the Madden-Julian Oscillation, ENSO, and atmospheric waves) to changes in land hydrology, ocean salinity, or climate feedbacks (e.g., involving cloud changes).

SUPPORT OF CLIMATE MODELING INFRASTRUCTURE

To facilitate community-wide use of climate data, PCMDI established and now supports data standards, enabling general tools to be developed to access, ingest, and analyze data from various sources. PCMDI plays a leading role in maintaining the Climate and Forecast (CF) Metadata Standard (*http://cf-pcmdi.llnl.gov/*) that has been widely adopted for use by the climate research community.

To encourage analysis of CMIP results, PCMDI supports development of software to enable users to search and retrieve CMIP data distributed across data nodes around the world. In this regard, PCMDI is responsible for the first widespread application of the Earth System Grid Federation infrastructure (*http://pcmdi9.llnl.gov/esgf-web-fe/*). In addition, PCMDI has nurtured the development of a rich set of DOE-supported analysis tools (currently known as Ultra-scale Visualization Climate Data Analysis Tools,



Analysis of surface salinity changes from 1950 to 2000 show that some regions are becoming saltier and others fresher, consistent with changing precipitation patterns. (Source: Durack et al., Science, 2012)

http://uv-cdat.llnl.gov/), designed to capitalize on the data standards established for CMIP output.

FUTURE DIRECTIONS

Building on its success in promoting comprehensive evaluation of climate models through intercomparison projects like CMIP, PCMDI now contributes in additional ways. For example, PCMDI, in collaboration with the National Aeronautics and Space Administration, helped establish a new activity called Obs4MIPs, which aims to make observational products more accessible for climate model intercomparisons (*http://obs4mips.llnl.gov:8080/wiki/*). This project facilitates evaluation of models by encouraging processing and archiving of observational data in conformance with the CMIP model output standards. In addition, PCMDI explores ways model quality information can be conveyed more widely to the research community, by, for example, leading an internationally recognized metrics panel working to establish a suite of standard metrics that will be used to monitor changes in performance as models evolve. Once established, these metrics—backed by standard diagnostic procedures and a library of analytical tools—will provide the basis for routine and transparent benchmarking of model development. The aim is to distill the information derived from the expanding community effort devoted to climate model analysis and to communicate those insights that might be of special interest to the groups attempting to improve the models.

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CAPT: THE CLOUD-ASSOCIATED PARAMETERIZATIONS TESTBED

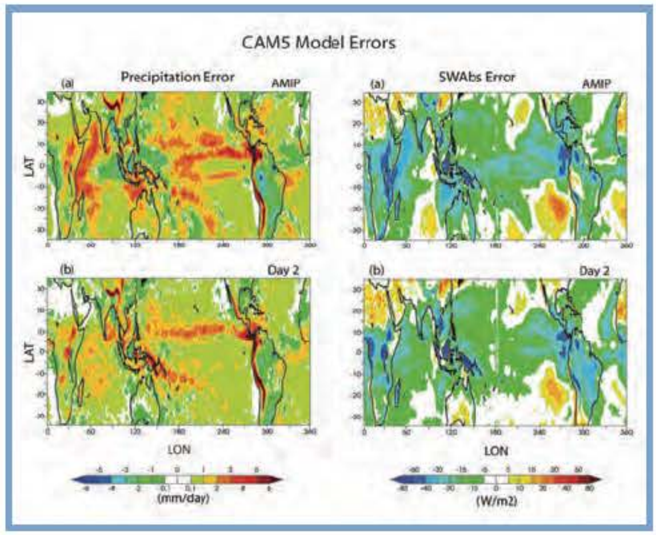
Despite the many advances made in climate modeling, large systematic errors are still present in their simulated mean state of climate. However, fully understanding the cause of these systematic errors in a climate system is difficult because the climate is a complicated non-linear system, and even a good simulation could result from compensating errors in representing various dynamical and physical processes. To address this problem, a team of researchers at Lawrence Livermore National Laboratory, in collaboration with scientists at the National Center for Atmospheric Research, has been working to diagnose the sources of these errors—many of which are known to result from imperfect representation of clouds in climate models.

CAPT
Cloud-Associated Parameterizations Testbed

For almost 10 years, the Cloud-Associated Parameterizations Testbed (CAPT) project has been diagnosing parameterization-related errors in the atmospheric models used for climate prediction. CAPT uses the unique technique of performing weather forecasts—actually hindcasts—with climate models. Simply stated, realistically initialized climate models are integrated in forecast mode to determine their initial drift from observations, thereby gaining insights on model parameterization deficiencies. The hindcasts are particularly effective:

- to diagnose the origins of errors in simulated climate
- to more effectively compare climate models to point observations such as those collected at ARM sites
- to assess the relative strengths and weaknesses of alternate parameterizations of atmospheric physical processes—particularly those associated with cloud processes.

CAPT is sponsored by the U.S. Department of Energy's Office of Science through the Regional and Global Climate Modeling and Atmospheric System Research programs.



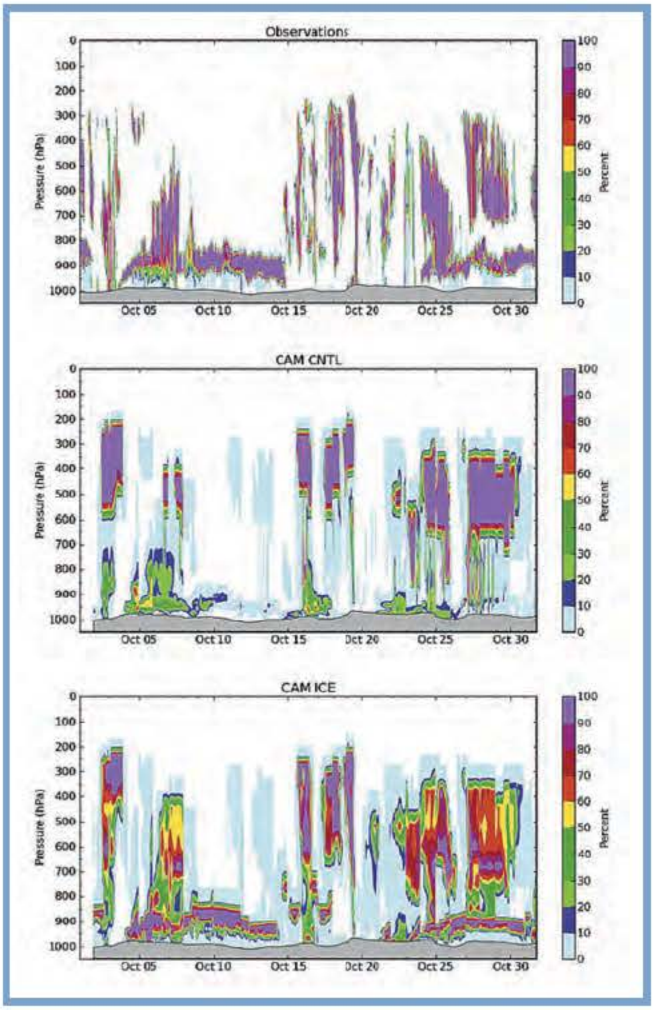
Error in precipitation and absorbed solar radiation simulated by the Community Atmosphere Model in weather-prediction mode ("Day 2") bear a striking resemblance to the errors simulated by the free-running model ("AMIP"). This correspondence suggests that many climate model errors in clouds and related processes result from an incorrect representation of the cloud-associated parameterizations and that they can be diagnosed with an economical weather forecast approach. (Source: Xie et al., 2012)

MANY FORECAST ERRORS ARE CLIMATE ERRORS

The mean errors in hindcasts bear a striking resemblance to climate errors. This is particularly true for precipitation errors in the tropics and the overestimate of net shortwave absorbed radiation in the stratocumulus cloud decks over the eastern subtropical oceans. This tells researchers that these errors result from errors in the fast cloud processes and are not the result of errors in simulating the large-scale state of the atmosphere. Some errors, such as the double Intertropical Convergence Zone, are not apparent in the hindcasts, suggesting these result from long-time feedbacks with the large-scale circulation. Studying the error growth in hindcasts helps to understand what model components need fixing.

ARM PROVIDES CRITICAL OBSERVATIONS TO TEST MODELS

Sometimes critical data to test the simulation of clouds in models are available only from special observations at only a few locations. Integrating climate models in weather-forecast mode much more readily facilitates the comparison of models to these observations. An example of this is the records of the vertical occurrence of cloud observed by the cloud radar and lidar at the Atmospheric Radiation Measurement (ARM) Climate Research Facility sites, such as that at the North Slope of Alaska. The CAPT project has performed extensive comparison to ARM data and helped modelers identify which parameterizations better simulate cloud and aerosol processes.



Time-height (pressure) cross-section of cloud frequency at ARM's North Slope of Alaska site during October 2004 from ARM cloud radar and lidar observations and two versions of the Community Atmosphere Model integrated as a weather-forecast model by CAPT. The ARM observations provide critical model tests and in this example show that when the parameterization of ice microphysics of CAM is modified ("CAM ICE") that the simulation of low mixed-phase clouds is improved relative to the default model ("CAM CNTL"), albeit with a degradation in higher level clouds. (Source: Gettelman et al., 2010)

INCREASING MODEL RESOLUTION HELPS BUT IS NOT A PANACEA

One approach to improve the simulation of cloud processes is to increase the model horizontal resolution. The CAPT project has been assessing the value of increasing the model horizontal resolution by asking which phenomena improve or whether further parameterizations would be more worthwhile. For tropical precipitation, the CAPT project has demonstrated improvements with resolution to the intensity distribution and land-sea breezes triggered by coastal circulations. However, increased resolution is not a panacea as the spatial patterns of global model biases in time mean precipitation are largely unchanged over resolutions, and in some regions, the 0.25° model significantly overestimates the observed precipitation.

FUTURE DIRECTIONS

To date, all CAPT integrations have been with only the atmosphere component of climate models. However, it is clear that errors in representing cloud processes contribute to errors in the climate simulated by fully interactive ocean-atmosphere models. Thus, CAPT will be extending the concept of weather forecasts from the atmosphere to the fully coupled ocean-atmosphere model. This will allow researchers to more effectively improve the simulation of climate in the models used for climate change prediction.

ACCOMPLISHMENTS

Since the inception of CAPT in 2003, the project has resulted in 25 published papers in 10 years. The pioneering work on the application of weather forecasting techniques to climate models has been cited in the fourth and fifth assessment reports of the Intergovernmental Panel on Climate Change. The team has tested many parameterizations over the years as a service to the community of scientists developing new parameterizations. Numerous parameterization tests have been used in the process to decide what parameterizations should be included in a climate model.

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IDENTIFYING ROBUST CLOUD FEEDBACKS IN OBSERVATIONS AND MODELS

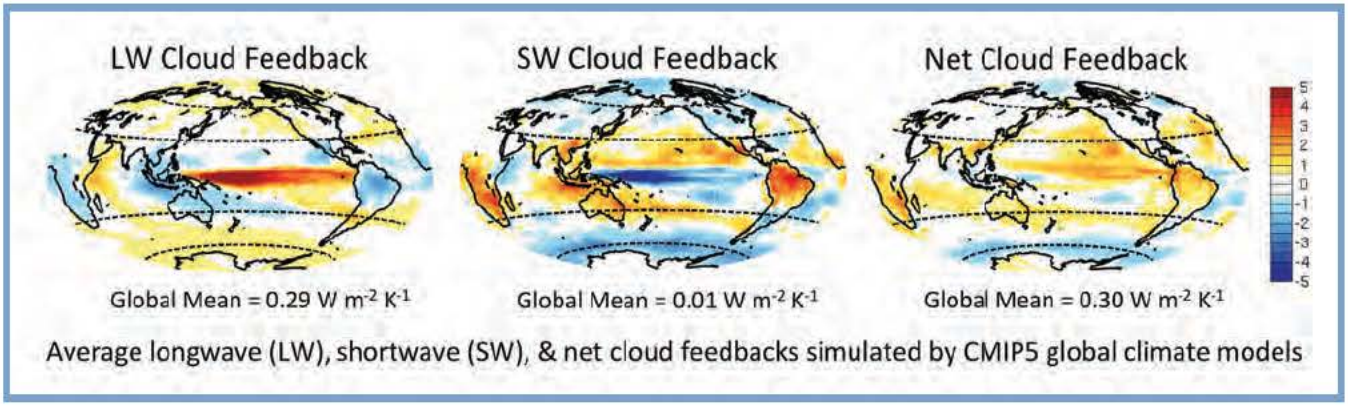
For more than 30 years, scientists have known that the inability to predict how clouds will respond to climate change hinders a confident prediction of the magnitude of global warming resulting from a given increase in greenhouse gases. As a result, they are not able to confidently identify the magnitude of carbon emission reductions necessary to avoid dangerous human influences in the climate system. Thus, research is needed aimed at reducing the uncertainty range associated with the response of clouds to a warming of the planet, also known as the "cloud feedback."

How clouds respond to climate change is one of the key uncertainties in the prediction of future climate. Research is needed to narrow the range of uncertainty due to the cloud feedback so that policy makers can understand how much climate warming will result from a given level of greenhouse gas emissions.

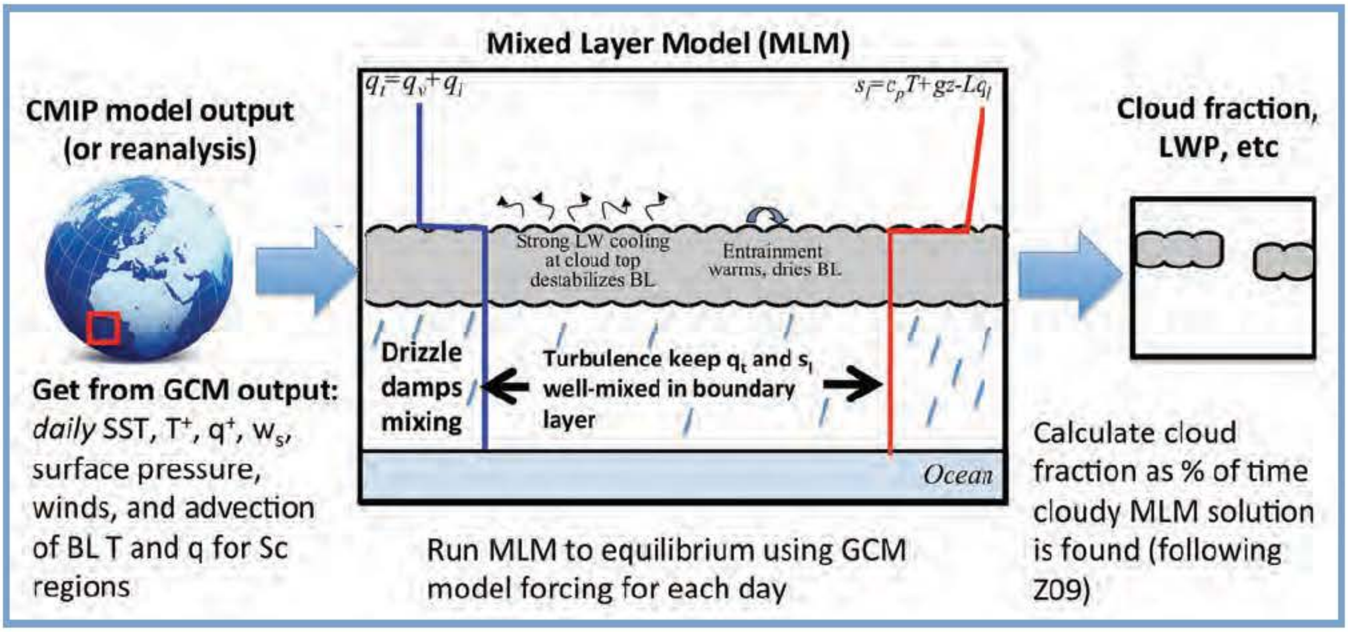
In a project sponsored by the U.S. Department of Energy's Office of Science through the Regional and Global Climate Modeling program, a team of researchers at Lawrence Livermore National Laboratory and the University of California at Los Angeles are working to reduce these uncertainties by identifying robust cloud feedbacks in today's climate models and constraining them with available observations. The team scrutinizes the results from simulations of future climate made by the most recent climate models assessed by the Intergovernmental Panel on Climate Change to answer a variety of questions:

WHICH CLOUD TYPES MATTER FOR CLOUD FEEDBACK?

Cloud feedbacks are extremely variable between different climate models. It is not always clear what is the relative contribution of cloud types from various regions to the global mean cloud feedback and its inter-model spread. Researchers in this project have developed novel techniques to separate the contribution of different cloud types and have found that cloud feedbacks are not the result of a single cloud type, but researchers must consider feedbacks from many cloud types including low clouds, high clouds, mid-latitude clouds, and polar clouds.



Cloud feedbacks simulated in the latest (CMIP5) global climate models. Positive feedbacks (red colors) amplify warming and negative feedbacks (blue colors) dampen warming. Cloud feedbacks result from a wide variety of clouds in diverse climate regimes globally. This requires research aimed at understanding of the responses of various cloud types across the globe to climate change. (Source: Zelinka et al., 2013)



Simplified process models driven by boundary conditions from global climate models provide insights in the reasonableness of cloud feedbacks simulated by global climate models. In this case, a Mixed-Layer Model (MLM) is used to understand how one of the key cloud types —namely, low clouds over the subtropical oceans—responds to climate change. (Source: Caldwell et al., 2013)

WHAT ASPECTS OF CLOUD FEEDACK CAN BE CONSTRAINED WITH TODAY'S OBSERVATIONS?

A key aspect of the project is the identification of cloud feedbacks where similarities are found in simulations of both current-climate variability and of projected climate change (so called "timescale invariant feedbacks"). For example, if fluctuations of clouds with day-to-day, or season-to-season, variations of temperature are similar to those shown over climate change time-scales, observations from the current climate could be used to constrain cloud feedbacks. Researchers are working to identify which cloud types exhibit time-scale invariance as well as the observations that can quantitatively constrain these feedbacks.

WHAT PHYSICAL PROCESSES CONTRIBUTE TO CLOUD FEEDBACK AND WHAT FEEDBACKS ARE CORRECT?

Our confidence in any given cloud feedback is dependent on our ability to understand the physical processes from which the feedbacks result and our confidence in those processes. Researchers are working towards identifying the physical mechanisms of various feedbacks simulated by complex climate models and critiquing their realism. One technique to accomplish this is the application of more realistic models of cloud processes to the changes in the large-scale environment predicted by global climate models.

ACCOMPLISHMENTS

Since the inception of the project in 2010, the project has resulted in 8 published papers. Results from some of these papers have been cited in the 5th Assessment Report of the Intergovernmental Panel on Climate Change. Our novel techniques to diagnose cloud feedbacks have been shared with the international research community and facilitate a wide variety of studies.

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Lawrence Livermore National Laboratory Science Focus Area Mission

To advance model-based climate prediction to meet the needs of DOE, the nation, and the world through quantitative diagnostic analysis of earth system model simulations.

10-Year Vision

We will continue to be an internationally renowned center of excellence with a leadership role in evaluating models of the Earth system, intercomparing model results, developing innovative climate simulations and diagnostic methods, and examining and reducing uncertainty in the key feedback processes affecting climate projections.

10-Year Goals

1. Determine the relative contributions of natural and anthropogenic forcing agents and internal variability to observed climate change.
2. Foster coordinated community efforts to diagnose and quantify the causes of inconsistencies between the simulated and observed climate, accounting for current uncertainties in both.
3. Determine the real-world cloud feedback on climate change for all radiatively important cloud types.
4. Reduce uncertainty in climate projections by identifying and quantifying relationships between model fidelity in simulating past and contemporary climate and the changes they predict for the future.
5. Improve simulation accuracy through better cloud representations in climate models.

Approach

- Exercise continued leadership in developing and supporting coordinated international climate model intercomparison projects.
- Analyze results from multi-model ensembles to quantify, understand, and reduce uncertainty in forcing estimates, climate model projections, and observations.
- Champion community development of and contribute to a diverse suite of metrics for assessing climate model simulation fidelity and prediction accuracy.
- Improve cloud parameterizations through a testbed that integrates hindcast simulations with process-level observations.
- Constrain cloud feedbacks with observations where multi-model ensemble simulations indicate that present-day observables are informative of the climate change response of clouds.

Additional Discussion of 10-Year Goals

Goal 1: The reliability and usefulness of model projections of future climate change depend on how well they can predict observed climate change and how well we understand the various causes of climate change. Thus, we have a 10-year goal to explain observed climate change by determining the relative contributions of natural and anthropogenic forcing agents along with the "noise" of unforced variability. We will rely largely on detection and attribution "fingerprint" techniques pioneered at LLNL by Ben Santer, which increasingly are based on multi-model results and multiple observational products. An essential component of the research will be evaluating whether model unforced variability is consistent with observations, which is challenging because in observations it is difficult to isolate the various contributions to variability. As in our past research, we expect to collaborate with modeling groups at NCAR and elsewhere to encourage new simulations needed to address this goal.

Goal 2: From its beginning, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) has championed coordinated modeling activities worldwide to promote a more systematic and comprehensive evaluation of the models and to provide a multi-model perspective of their projections. The value and impact of this work is evident from the thousands of papers that rely on "model intercomparison" results from projects such as the Coupled Modeling Intercomparison Project (CMIP), which has played a key role in recent assessment reports of the Intergovernmental Panel on Climate Change. The 10-year goal of LLNL in exercising ongoing leadership of this kind will be to foster coordinated community efforts to understand the causes of inconsistencies between the simulated and observed climate. PCMDI will focus on evaluating model simulations of the mean, seasonally varying climate and on changes in climate over the data-rich recent few decades. Major components of the climate system (atmosphere, ocean, sea ice) will be scrutinized. Where systematic errors in models are identified, additional analyses will be performed to diagnose the root causes. As an integral part of all evaluations, the limitations of observations will be characterized.

Goal 3: For more than 30 years, the uncertainty range in equilibrium climate sensitivity has remained stubbornly large, with estimates ranging from 2 to 5 Kelvin for a doubling of carbon dioxide. It is well known that the leading cause of uncertainty in equilibrium climate sensitivity estimates is the radiative feedbacks of clouds to climate warming. The 10-year goal of LLNL in Cloud Feedback research is to determine the true cloud feedback on climate change for all radiatively important cloud types. We will accomplish this goal through intensive diagnosis of model simulations of climate change combined with creative use of observations to determine the true values of feedbacks of individual cloud types. Determining long-term climate feedbacks from present-day observations is pursued through the emergent constraint technique that was first demonstrated by Professor Alex Hall (UCLA), who is a participant of LLNL efforts in Cloud Feedback research.

Scientists at LLNL are particularly well-positioned to determine the true cloud feedback due to our pioneering of advanced techniques to diagnose model feedbacks such as cloud radiative kernels and satellite simulators, our deep knowledge of cloud processes in nature and their representation in models, and our extensive experience with multi-model ensembles of climate change simulations through our leadership in collaborative international modeling efforts such as CMIP and the Cloud Feedback Model Intercomparison Project. In addition to determining the true cloud feedback, we will work to determine how cloud feedbacks will be manifest in long-term trends of the real-world climate system relative to natural climate variability. We will also work to determine how climate models need to be modified in order to correctly simulate cloud feedbacks. In sum, we will make major progress in reducing the uncertainty in the cloud feedback leading to improved predictions of the magnitude of climate change—allowing humans to better understand by how much greenhouse gas emissions need to be lowered to keep climate change under dangerous levels.

Goal 4: One benefit of establishing benchmark experiments as part of projects like CMIP is that metrics can be developed and routinely applied to monitor the fidelity of models as they evolve. All aspects of simulations deserve scrutiny, from the climatological seasonal cycle to the process-level behavior. Although cloud feedback processes are known to be important in explaining the range of model global mean projections, we have yet to determine what additional factors are critical for accurately predicting regional and seasonal changes in climate. Thus, we have a 10-year goal to reduce uncertainty in climate projections by identifying and quantifying relationships between model fidelity in simulating present-day climate and the changes they predict for the future. We expect to make progress toward this goal by developing and encouraging community development of metrics that characterize model fidelity over a wide range of time and space scales and that quantify the accuracy with which models represent the multitude of processes that determine climate. Relying on simulations of present and future climate by CMIP models, we will attempt to determine which aspects of the simulation of present-day climate are most important for accurate projections of climate change, and we will use this to narrow uncertainty in projections.

Goal 5: Although the simulation by climate models of clouds and associated processes such as radiation and precipitation has improved in recent decades, errors remain too large to substantially narrow the uncertainty in model predictions of climate variability and change. The 10-year goal of LLNL's Cloud-Associated Parameterizations Testbed (CAPT) project is to improve the representation of cloud processes in climate models via a testbed combining hindcast simulations with process-level observations. The use of process-level observations is an integral part of improving climate model simulations because it is through the model-observational comparison process that one identifies the targets (metrics) for model simulation and one can develop creative ideas as to how cloud parameterizations may be improved. Key to model-observation comparisons are advanced diagnostics such as those provided by the "satellite-simulator" technique (developed in part by CAPT scientists) that facilitates a detailed comparison of model cloud properties with satellite observations. Hindcast simulations facilitate comparison to observations such as those collected by DOE's Atmospheric Radiation Measurement Climate Research Facility and encourage an examination of time-step level output. Hindcast simulations also allow for diagnosis of the growth of errors that contribute to long-term model biases.

With many years of experience, CAPT scientists have performed comparative hindcast simulations with new cloud parameterizations to identify the relative strengths and weaknesses of the different ways in which cloud processes can be represented. While CAPT contributes to international multi-model intercomparison projects featuring hindcast simulations, such as those organized by Global Energy and Water cycle EXchanges (GEWEX) and Transpose-AMIP, CAPT's impact is maximized by focusing on a single climate model and collaborating closely with its model developers. In the past, CAPT focused on the NSF/DOE Community Atmosphere Model, but in future CAPT will focus on DOE's Accelerated Climate Model for Energy. Over the next 10 years, CAPT will meet the continued needs for testing of cloud parameterizations, particularly as model resolution increases to the point where traditional cloud parameterization assumptions break down. CAPT will also pursue diagnostic studies that aim to better identify the contribution of errors in cloud and associated atmospheric processes to biases in surface climate in fully coupled climate models. Through these efforts and as part of the community of model developers, CAPT will improve the representation of cloud processes in climate models, contributing to increased accuracy in model simulations of climate variability and change.

UCAR Cooperative Agreement

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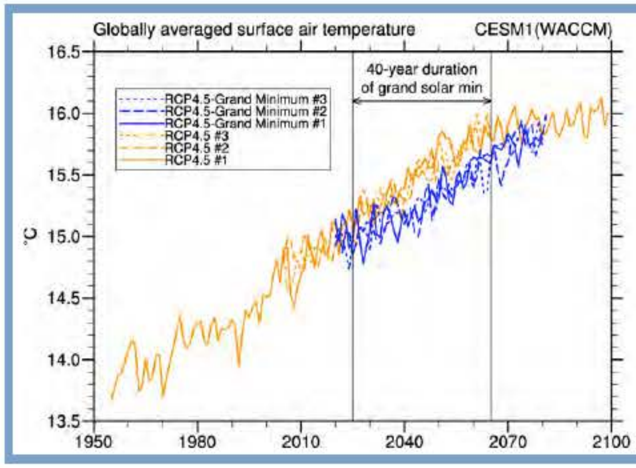
A COOPERATIVE AGREEMENT TO MODEL FUTURE CLIMATE CHANGE

The U.S. Department of Energy (DOE) has supported climate change research at the National Center for Atmospheric Research (NCAR) since 1978. A DOE/UCAR Cooperative Agreement for the Regional and Global Climate Modeling Program has been in place since 1997 with DOE's Office of Science and the University Corporation for Atmospheric Research (UCAR) to model future climate change and conduct extensive analyses into how the climate system responds to various climate forcings. This research also evaluates and improves components of climate and Earth system models, performs process studies using model versions of varying complexity and resolution, and applies climate dynamics to climate change. One unique contr bution is its role within the Climate Variability and Change Working Group in connection to the Community Climate System Model/Community Earth System Model (CESM). On average, this project produces 30 peer-reviewed papers each year. To ensure Cooperative Agreement science is integrated into national and international research agendas, scientists play leadership roles in the CESM, World Climate Research Programme, National Research Council, and in climate assessments. Climate change simulations performed as part of the Cooperative Agreement have made major contributions to the Intergovernmental Panel on Climate Change assessment reports.



Time series of globally averaged surface air temperature anomalies (°C) relative to the 1986-2005 reference period for the CESM1(WACCM) standard RCP4.5 simulations (orange lines) and the grand solar minimum experiment (blue lines). The duration of the grand solar minimum experiment is indicated from 2025-2065.

SCIENCE QUESTIONS ADDRESSED

- How can we better quantify certainty of long-term climate change? How is certainty related to the factors that produce spread in future climate change projections?
- What is the time evolution of the statistics of regional climate over the next decades?
- How will future hurricanes and tropical cyclones behave, and how will regional precipitation and temperature extremes evolve in the future?
- How much and how fast will sea-level rise, both globally and regionally?
- What processes determine the response of the hydrological cycle to future greenhouse forcing, and how do these atmospheric moisture processes determine the spatial distribution of surface precipitation and evaporation?
- How do these moisture feedback factors depend on model horizontal resolution?

TASK 1: RESEARCH PROGRAM ON MODELING FUTURE CLIMATE CHANGE: EFFECTS OF INCREASED ATMOSPHERIC CARBON DIOXIDE AND OTHER CLIMATE FORCINGS

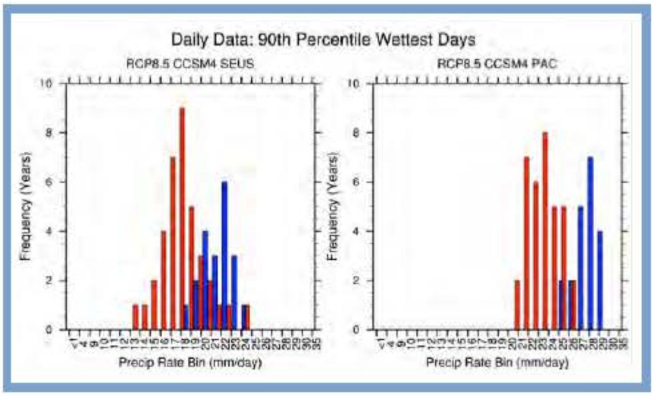
Led by: Warren Washington and Gerald Meehl, Principal Investigators

State-of-the-art, global, climate and Earth system models are employed to address future climate change in the context of the natural variability of the atmosphere, ocean, sea-ice, land/vegetation, hydrological and carbon cycle components of the Earth system. Research includes identifying spatial and temporal patterns in model results that are associated with climate change, especially on regional scales. This task seeks to identify the dynamical processes that produce these patterns and to provide an interpretation of the model projections. For example, a future decrease of solar irradiance is shown to slow down, but not stop, global warming.

TASK 2: FUTURE CHANGES IN EARTH'S ATMOSPHERIC HYDROLOGICAL CYCLE AND THE RESPONSE OF ECOSYSTEMS TO CLIMATE CHANGE

Led by: Jeffrey Kiehl, Principal Investigator

Simulations of CESM are analyzed for both present and future climates to quantify the relative contr butions of various dynamic



Extreme precipitation events comparing the standard fully-coupled CESM 1° (blue) and 0.5° (red) atmosphere/land model coupled to a 1° ocean/ice model. Extreme precipitation is computed by finding the 90th percentile for wettest days for each year. Histogram frequencies represent one event as the average of each year's wettest days, i.e., the max frequency is 20 (years).

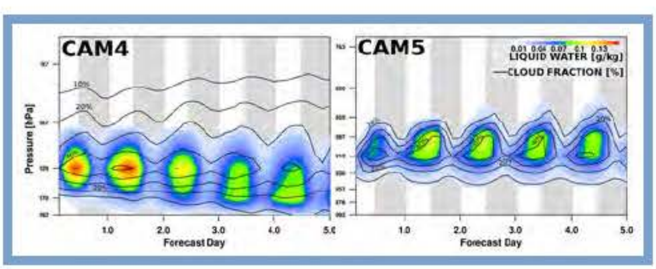
and thermodynamic processes acting as feedbacks to the hydrological cycle in Earth's climate system. Present-day climate simulations are compared to a collection of observations–satellite and surface-based–to quantify the accuracy of the CESM simulated hydrological processes. Changes in specific humidity, cloud properties, transports, and overall moisture budgets are compared for the various forcing agents applied in future climate simulations.

The standard fully coupled CESM 1° resolution model compared to a version of moderately higher resolution (0.5° atmosphere/land) translates into the half-degree version producing wetter days with more extreme values.

TASK 3: EVALUATION OF AND IMPROVEMENTS TO COMPONENTS OF CLIMATE SYSTEM MODELS

Led by: David Williamson, Richard Neale, and Brian Medeiros, Principal Investigators

Under this task, research involves examining, evaluating, and improving coupled models and model components in an attempt to verify both the processes and resultant stationary and time-varying climate phenomena. These include the numerical approximations for fluid flow on the sphere (through methods of establishing their validity and desirability rather than actually developing the methods themselves), the complete suite of sub-grid scale parameterized processes for the individual components, and the coupling of all these components (through experiments in simplified regimes such as aqua-planets). Compared to CAM4, the new CAM5 model has substantially revised cloud physics, leading to a more realistic cloud structure with clear layers below and above a well-defined cloud layer. Both models show a daily cycle of cloud cover with more clouds at nighttime and a thinning cloud layer during the daytime that is in general agreement with observations.

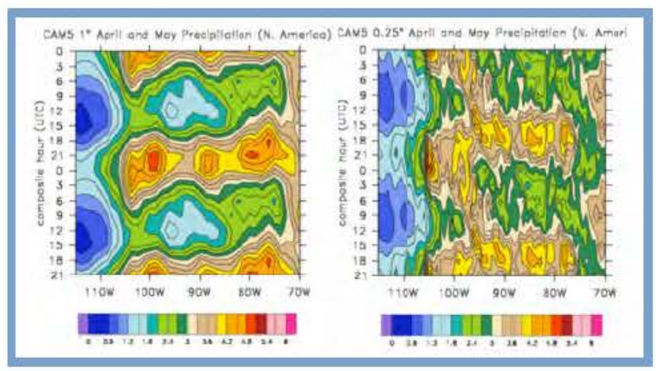


A month of cloud forecasts of the subtropical southeast pacific are combined to show the composite five-day forecast, with the older CAM4 on the left and the newer CAM5 on the right.

TASK 4: CLIMATE MODELING WITH MESOSCALE ATMOSPHERIC VARIABILITY AND SCALE-AWARE PHYSICAL PARAMETERIZAONS

Led by: Joe Tribbia, Principal Investigator; Sungsu Park, Co-Investigator

A comparison of global, mesoscale-resolving models (1/4° – 1/8° resolution in the atmosphere and 1/10° resolution in the ocean) with the standard 1° resolution coupled climate simulations and projections is used to understand and quantify limitations and uncertainties. Such coupled climate models that include mesoscale variability in the atmosphere and ocean are now usable because of the increase in computer power over the last five years. The challenge of this research task is to understand and use atmospheric models with advanced physical parameterizations.



Precipitation composited by hour for the spring season over North America for CAM5 1° (left) and CAM5 0.25° (right). The propagating precipitation in the 0.25° composite precipitation is orographically driven by the Rocky Mountains, which does not occur at the coarser 1° resolution.

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UCAR Cooperative Agreement Summary

The 10-year vision for the DOE/UCAR Cooperative Agreement (CA) involves five general science topics with a set of comprehensive and ultimately challenging science questions that set the course for CA research for the next ten years. The 3-5 year vision and actionable items include model simulations, analyses, and model developments to help realize that 10-year vision.

The USGCRP strategic plan highlights four key global change strategic goals: 1) advance science, 2) inform decisions, 3) sustain assessments, and 4) communicate and educate. Our primary focus in the CA is on 1, advance science; however, we also contribute to goal 2 (inform decisions) and goal 3 (sustain assessments). Thus, the CA directly addresses the DOE BER research mission to understand complex biological, climatic, and environmental systems across spatial and temporal scales.

Over the next 10 years, the CA will address the overarching goal of BER to provide the foundational science to understand the potential effects of greenhouse gas emissions, particularly fossil fuel emissions, on Earth's climate and biosphere, and the implications of these emissions for our energy future.

More specifically, the CA research vision is to run and analyze climate and earth system models along with observations to enhance understanding, predictive skill, and predictability at regional and global scales. This is closely aligned to the RGCM strategic goal, and in particular the CA will perform research pertaining to the five science foci of RGCM: CVC and cloud processes, high-latitude feedbacks, water cycle, extremes, and analysis of BGC feedbacks.

10-Year Vision

Science Topic 1: Near-Term Decadal Climate Predictability, Prediction, and Long-Term Climate Projections

Science questions for topic 1:

Using analysis of observations and model simulations, what are the relative contributions of internally generated decadal timescale variability and externally forced response to the observed time evolution of global, regional, and local climate on decadal timescales?

What are the processes and mechanisms in the climate system that produce internally generated climate variability (e.g., IPO/PDO, AMOC) and how does climate change affect those internal processes and mechanisms?

Can decadal processes and mechanisms, if properly initialized, provide increased prediction skill, reliability, and probabilistic climate change information regarding the time evolution of global, regional, and local climate in the near term, over and above that from the externally forced response? What is the source of predictability (e.g., model initialization of atmosphere, ocean, land, cryosphere) of subseasonal to seasonal to interannual to decadal global/regional/local climate and extremes?

How will global, regional, and local near-term climate evolve differently from the long-term externally forced response, particularly in the context of mitigation scenarios?

Science Topic 2: Predicting Extremes

Science questions for topic 2:

Can we use initialized models to predict decadal regimes of extremes and relate that to long-term, base-state climate changes (e.g., hurricanes, droughts, etc.), and how does this relate to the connections between weather and climate in terms of models and observations (e.g., atmospheric rivers and water cycle)?

Framing extremes in terms of record-setting events that we have already observed, how and in what regions and localities will record-setting temperature, precipitation, droughts, and floods occur and what are the processes and mechanisms that will affect the predictions for the near term and long term?

What will be the near-term and long-term regional/local extremes of sea-level rise particularly associated with storm surges from mid-latitude and tropical storms, and how will the Greenland and Antarctic ice sheet melts directly affect AMOC and regional/local sea-level rise?

Science Topic 3: Comprehensive Characterization of Uncertainty Using a Hierarchy of Models

Science questions for topic 3:

What would be the elements of a robust and comprehensive uncertainty characterization and quantification of both the physical climate changes and their societal/natural system impacts?

How will non-paramaterized clouds impact our understanding of long-term climate change, our confidence in projections, and our understanding of uncertainty, and how would those results relate to those from lower-resolution models that can be run for more and longer experiments to characterize uncertainty?

What is the best methodology for a multi-model framework to exploit a hierarchy of models with deliberate experimental designs and statistical approaches (emulators/pattern scaling) to better explore uncertainties within and across models?

Science Topic 4: Land Surface Processes and BGC Feedbacks

Science questions for topic 4:

How will climate change affect vegetation, and what are the size and nature of associated carbon-cycle feedbacks in the climate system?

What is the impact of land management on climate as well as carbon and water cycles, and what is the potential for climate mitigation and reduction of stresses on resource availability through land management strategies?

What is the role of plant hydraulics in drought, soil moisture stress, plant mortality, and water resources?

With regards to permafrost, is rapid mobilization of carbon possible (and how important is it) due to landscape thermokarst/thaw slumping, and other processes?

Science Topic 5: Atmospheric Model Improvements

Science questions for topic 5:

What is the sensitivity of a climate model to resolution, and do feedbacks (e.g., clouds, water vapor) function differently at different model resolutions?

What is the best application of variable in the short term, pointing to longer-term variable resolution, cloud- and convection-resolving regions within a coarse-grid GCM, and transition to city-scale atmospheric and land representation (global to regional to local)?

How can CESM modularity with multiple parameterizations or fast physics/emulator components be best employed to explore the climate system response to forcings?

What is the best use of idealized frameworks in the model hierarchy, such as aquaplanets, radiative-convective equilibrium, single-column models, specified dynamics, and short-term forecasts, to quantify the role of model resolution (e.g., high resolution) in climate system response and feedbacks (e.g., cloud feedback), with the goal of reducing model systematic errors?

3-5 Year Vision and Actionable Items

Perform CESM1 and CESM2 initialized hindcasts and predictions (DCPP CMIP6).

Perform DCPP coordinated process experiments for CMIP6.

Perform high-resolution global coupled climate model simulations (run and analyze CESM, analyze ACME simulations as available) long control runs and 20th- and 21st-century simulations with coupled ice sheets.

Perform ScenarioMIP simulations with CESM2.

Perform perfect model predictability studies and real-event case studies.

Perform analysis of model simulations at 1°, 0.5°, and 0.25° resolutions to study the processes and mechanisms associated with atmospheric rivers and water cycle.

Build better statistical models for climate change at regional scales and impacts, interpolating results across scenarios, linking large-scale and better-understood changes to regional-scale and impact-relevant quantities, and translating these changes to global-scale impacts (e.g., human exposure to extremes; food security).

Run and analyze large ensembles/perturbed physics/CMIP5 and then the CMIP6 output, and build on the knowledge of those analyses to target experimental designs choosing both scenarios and model configurations (high-res/cloud resolving) to better inform both adaptation and mitigation decisions in the short/mid/long term.

Incorporate ecosystem demography in the CESM.

Improve convection: sub-grid-scale PDF convective parameterizations, and non-hydrostatic assumptions to improve precipitation forecasts.

IAMs/urban model: embedded 2D urban representations, 2-way coupling to IAMs for end-to-end climate projections from societal assumptions to emissions to carbon to impacts to feedbacks (connect to DOE IA Research Program).

Perform, as standard, simulations using emission-driven version of CESM.

Perform CFMIP simulations (in collaboration with Livermore).

Perform detection/attribution MIP experiments (in collaboration with PCMDI).

Perform ScenarioMIP simulations with CESM (in collaboration with all SFAs and DOE IAM program).

Perform LS3MIP and LUMIP (in collaboration with other SFAs).

Include in CESM various land management methods (e.g., agriculture including irrigation, fertilization, tillage, and cultivation; forestry; water impoundment).

Continue development of representation of land management (and relevant underlying biogeophysical and biogeochemical processes) within CESM land models; tie in with LUMIP (Land Use Model Intercomparison Project, CMIP6).

Leverage and expand ILAMB to assess ability of models to represent the impacts of land management on carbon, water, and energy cycles.

Include plant hydraulics in CESM to accurately represent drought effects on vegetation dynamics now and in the future, thus leveraging ILAMB activities.

Push model resolution (e.g., grid spacing less than 10 km) to reduce atmospheric model systematic errors by explicitly resolving convective updrafts and cloud-resolving processes, though even at 10-km grid spacing, cloud parameterizations will still be present to deal with microphysics, turbulence, and small-scale clouds like shallow cumulus and stratocumulus.

Develop model configurations and diagnostic approaches to explore and evaluate high-resolution simulations (25-10-km grid spacing) within CESM, providing a solid foundation for full-scale climate simulations with reduced systematic errors.

Conduct detailed evaluation of developmental versions of CESM under idealized conditions, including sensitivities to dynamical core, parameterized physics, numerical implementation, and resolution.

Develop a hierarchy of modeling configurations to explore and evaluate high-resolution CESM simulations, including the coupled context.

Quantify and understand process-level and climate feedback processes in high-resolution simulations.

Core Scientific and Technical Capabilities

The DOE BER-supported research through the CA provides a unique and direct DOE BER and RGCM link to the CESM Climate Variability and Change Working Group (CVCWG) through the DOE-funded Climate Change Prediction (CCP) group at NCAR. The CCP/CVCWG is the only group officially tasked to perform the large number of standard climate change simulations with CESM (e.g., CMIP5 simulations that were assessed in the IPCC AR5, U.S. National Climate Assessment, etc.) at multiple DOE- and NSF-funded supercomputer centers (e.g., NERSC, Argonne, NCAR, etc.). The CCP group will be running CESM for the

CMIP6 simulations. CCP then performs diagnoses of the climate-change simulations not only with the CESM suite of experiments, but also compared to larger multi-model data sets such as CMIP5. CCP also performs one-of-a-kind sensitivity experiments with a hierarchy of models in the CESM suite to diagnose processes and mechanisms of climate variability and change. Thus, one unique technical capability of the CA to RGCM and BER is this combination of performing climate change experiments with CESM for the community, the diagnosis of those experiments, and the performance of additional sensitivity experiments with the models to focus on particular processes and mechanisms to learn more about climate variability and change.

In addition, CA-funded scientists and software engineers have the capability and expertise to effectively use existing supercomputers in efficiently running many ensemble members with a hierarchy of models to address climate variability and change and to characterize uncertainty. CCP not only makes these runs, but processes and archives the model output for access by DOE and CESM scientists and the climate science community at large.

Another unique core scientific and technical capability of the CA is research on improvements to the atmospheric component of CESM. While other elements of DOE and NSF support improvements to the different components of the model, CA-funded scientists focus uniquely on theory and observations to improve the simulations provided by the atmospheric component. This produces higher-quality and more credible simulations of the entire CESM, of which the atmosphere is a crucial part, and where many of the important feedbacks of the climate system are managed.

Gaps that Could Be Complemented by Other Projects

Studies of sea-level rise in all its aspects will require credible land ice models incorporated in CESM.

Aspects of land surface and carbon cycle will require collaboration with DOE-funded SFA activities.

Climate change detection/attribution studies would benefit from collaboration with PCMDI.

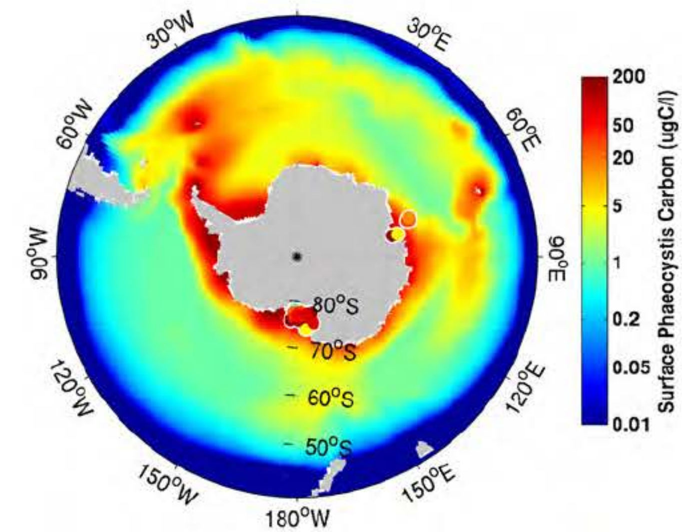
Cloud feedbacks and analysis of CFMIP simulations that we will perform for CMIP6 could benefit from collaborations with Lawrence Livermore National Laboratory.

High Latitude Application and Testing of Climate Models (HiLAT)

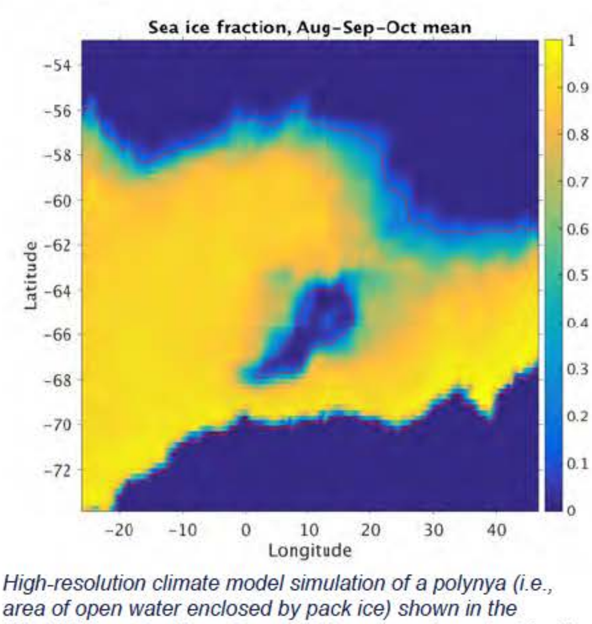
HIGH LATITUDE APPLICATION AND TESTING OF CLIMATE MODELS (HiLAT)

The climate of polar regions is changing faster than anywhere else on Earth. Permafrost degradation, collapsing ice shelves, and retreating sea ice all made headlines in recent years, with consequences for coastal and Arctic energy infrastructures. Even more challenging are the feedbacks that these high-latitude changes have on the polar and global climate system in general, like the global carbon cycle and mid-latitude weather. A thorough understanding of the high-latitude climate system is critical for researchers to better understand the challenges and opportunities the polar regions provide.

The High Latitude Application and Testing of Climate Models (HiLAT) project was created to answer Arctic and Antarctic climate change questions through targeted application of global modeling and analysis capabilities to evolving polar processes and their impacts. Researchers will apply high-performance multi-scale models and analyze the results to better understand how changes in the high-latitude climate system respond and contribute to global climate change.



Simulated distribution of the plankton species Phaeocystis Antarctica displayed in the Southern Ocean (observations in dots). This high-latitude specialist is an important source of cloud-brightening aerosols.



High-resolution climate model simulation of a polynya (i.e., area of open water enclosed by pack ice) shown in the Weddell Sea, Southern Ocean. Polynyas are important for the formation of the densest water masses in the World's Ocean.

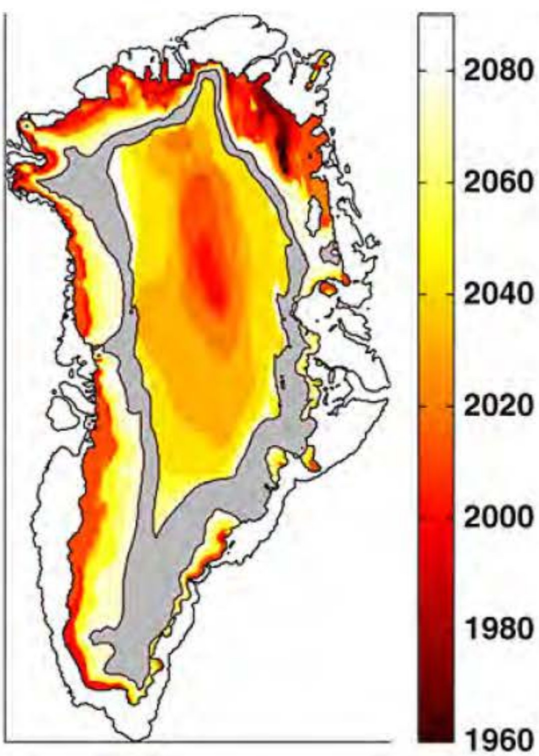
LOCAL AND GLOBAL CLIMATE CHANGES

Polar climate is highly complex due to the strong interactions between ocean, atmosphere, land, sea ice, land ice, and associated ecosystems. The multidisciplinary HiLAT team is taking an integrative approach to tackling some of the toughest climate problems. Researchers will use climate model simulations to quantify feedbacks between the cryosphere and the Earth's heat and water budgets to improve projections of high-latitude climate change and the resulting regional and global impacts.

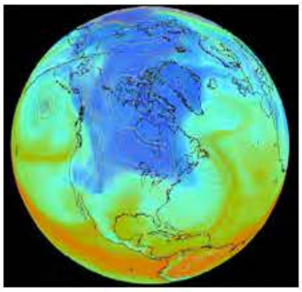
Several component studies will be performed to address sea ice predictability in the Arctic, Arctic delta evolution, and Greenland Ice Sheet behavior in a warming climate. These studies will address the regional and global impacts of these cryospheric changes, including atmospheric, oceanic and ecosystem responses.

Science questions include:

- Are changes in Arctic sea ice cover influencing mid-latitude weather extremes?
- How do recent changes in Arctic and Antarctic sea ice impact marine ecosystems, aerosol production, and the brightness of polar clouds?
- How do freshwater and nutrient inputs from ice sheets (e.g., Greenland and Antarctica) and Arctic rivers affect marine ecosystems and carbon sequestration?
- Does enhanced freshwater input from the Antarctic ice sheet play a role in the recent Southern Hemisphere sea-ice expansion?
- Will changes in Arctic Ocean circulation impact the Atlantic Meridional Overturning Circulation (AMOC), and affect decadal variability of the climate system?
- How will the Southern Ocean overturning and Antarctic Bottom Water formation respond to competing changes in atmospheric wind forcing, upwelling, sea ice changes, and fresh water inputs from ice sheets?
- Is polar amplification weaker in the Antarctic due to water vapor transport and lapse rate feedbacks resulting from changes in land mass and sea-ice distribution?



Year in which an anthropogenic signal can be detected from the surface mass balance of the Greenland Ice Sheet.



Water vapor and sea level pressure (contours) show the strong connectivity between the high and mid latitudes.

FUTURE DIRECTION

The HiLAT project will contribute to a better understanding of the complex interactions between the high latitude climate system components and how they will shape the evolution of climate system under continued anthropogenic forcing. The development of a new generation of climate models under DOE's Accelerated Climate Modeling for Energy (ACME) project will allow the team to address these issues with increasing level of detail and complexity. At the same time, continuing developments in uncertainty quantification will allow researchers to interpret model results in a more rigorous way.

HiLAT is a collaboration between scientists at the Los Alamos National Laboratory and the Pacific Northwest National Laboratory. This work is supported by the Regional and Global Climate Modeling program of the U.S. Department of Energy's Office of Science.

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High Latitude Application and Testing of Climate Models Introduction

The high-latitude regions of the Earth's climate system are immensely complex, with all major components of the climate system interacting in a web of feedbacks. Under continued anthropogenic forcing, the most dramatic changes in our climate system are found at high latitudes, and these changes in turn provide a significant feedback on global warming, e.g., through changes in albedo and cloudiness. High-latitude changes also have local and global implications for the nation and the Department of Energy (DOE). Sea-level rise affects coastal energy infrastructure; reductions in Arctic sea ice are leading to increased exploration for additional fossil fuel resources and to increased commercial transport through the Arctic; and warming at high latitudes appears to impact mid- and low-latitude weather and climate through changes in atmosphere and ocean circulation. Understanding and predicting the fate of the high-latitude climate system requires a strongly interdisciplinary approach. In this collaboration between LANL and PNNL, we propose to uniquely combine our strengths in ocean, sea ice, and ice sheet dynamics and modeling, ocean and sea ice biogeochemistry, atmospheric physics, and terrestrial hydrology in a concerted effort to tackle some of the toughest and most interdisciplinary climate change problems, with direct relevance for DOE and the nation.

10-Year Vision

Our 10-year vision is to quantify feedbacks between the cryosphere and the Earth's heat and water budgets to improve projections of high-latitude climate resulting in regional and global impacts.
We will focus our efforts on two closely related and highly integrative themes.

Theme 1: *identifying and quantifying feedbacks between cryospheric change and the regional physical and biogeochemical responses that result in rapid changes in the polar regions.*

For our first integrative theme, we will explore cryospheric changes and the high-latitude physical and biogeochemical **feedbacks that have local impacts**. High-latitude climate is driven by processes that affect local radiation balances (surface albedo, cloud characteristics, and greenhouse gas concentrations, including water vapor, liquid, and ice). Dynamical moisture, heat, and momentum transports to high latitudes also influence sea ice cover, ice surface albedo, and the uptake of carbon and emission of aerosols by marine ecosystems. Within the 10-year vision of this SFA, we plan to investigate some of these pressing issues, still largely unexplored, for the polar regions. We will evaluate the impacts of sea-ice changes, ice-sheet melting, river run-off, and ocean circulation on air-sea exchanges of biogenic aerosols and greenhouse gases. We will also investigate how altered biogeochemical cycles affect the atmospheric radiation budget and the subsequent feedbacks on the cryosphere, ocean, and atmosphere. Arctic sea ice retreat and Antarctic ice expansion are among the outstanding issues we intend to focus on.

Theme 2: *identifying and quantifying feedbacks between the polar region and global climate through cryosphere impacts on polar/extra-polar interactions.*

For our second integrative theme, we will explore feedbacks between polar change and the global climate system through cryosphere impacts on non-local climate features (i.e., polar/extra-polar interactions). The exchange of heat, freshwater and moisture, biogeochemical agents, and anthropogenic pollutants can all have significant impacts on the global climate. Within the 10-year vision of this SFA, we will focus on feedbacks among a changing cryosphere (sea ice and ice sheets), with subsequent impacts to ocean stratification, and a warming ocean, moving towards a state-of-the-science, eddy-resolving capability for the polar regions. We will also investigate feedbacks resulting from atmospheric changes, such as the meridional shift in zonal winds, changes in moisture transport from the mid-latitudes, and changes in precipitation patterns. Again, our 10-year vision enables critical investigation of mechanisms and global feedbacks associated with Arctic and Antarctic cryospheric change.

Years 1-3

For the first 3 years of the SFA, we have identified 7 science topics that we will address:

- The impact of sea-ice changes on the productivity of marine ecosystems, the subsequent implications for aerosol emissions; and the consequences for cloud brightness and the Earth's radiative balance;
- The competing impacts of freshwater and nutrient inputs by glaciers, ice shelves, and rivers on marine ecosystems; and again, the subsequent implications for aerosol emissions, and the consequences for cloud brightness and the Earth's radiative balance;
- Sea-ice expansion in the Southern Ocean, testing the hypothesis that glacial freshwater inputs are playing a role;
- Response of the Atlantic Meridional Overturning Circulation and its variability to changes in the freshwater balance of the Arctic and sub-polar North Atlantic Ocean;
- Response of Antarctic Bottom Water formation to changes in the freshwater balance of the Southern Ocean: in particular, to enhanced glacial inputs;
- Interaction between the polar and sub-polar atmosphere change under continuing reduction in Arctic sea ice, and the implications for water-vapor exchanges between the high and mid-latitudes; and
- The lapse rate feedback as a potential contributor to the large asymmetry in polar amplification.

Years 4-10

While we will start (in years 1-3) to address the hypotheses outlined above using the available versions of the CESM/ACME family of models (in particular the CESM clone ACMEv0.1), several aspects of the integrative themes cannot adequately be addressed by the current generation of models. We plan to address these themes more completely in later years by making use of ongoing and future model development efforts taking place through the ACME framework and RASM projects in addition to the experience we gain through the first 3 years of our project. In this section we list some of the science topics we intend to address in years 4-10 and briefly describe how our collaborations with ACME and RASM will advance model capabilities to enable this science.

Mesoscale Processes

A limitation of the current generation of global climate models is their inability to resolve some of the fine-scale processes that are critical for the high-latitude ocean, sea ice, and atmosphere systems. In particular, mesoscale eddies in the Arctic and Southern Oceans, which can be as small as a few kilometers, are important for ocean dynamics and tracer transports, both horizontally and vertically. It is therefore pertinent to ask: how will eddy variability in the Arctic and Southern Oceans change in response to a reduced sea-ice cover and the associated strengthening of air/sea coupling? How will an increase in stratification resulting from a strengthening hydrological cycle, melting ice sheets, and enhanced continental run-off affect eddy variability and vice-versa? How will such changes in eddy activity affect the statistics of vertical motions, and influence the supply of nutrients into the photic zone, and hence biological productivity? How will they affect the ventilation of warm subsurface water masses like the Atlantic Water in the Arctic and Circumpolar Deep Water in the Southern Ocean? Will the Arctic become an active site of deep convection and water mass formation?

Methane Cycle

In the first 3 years we will focus primarily on the impact of biogeochemical changes on aerosol production, and to a lesser extent on the sequestration of carbon dioxide. However, another powerful greenhouse gas is methane. The high latitudes play an important role in the methane cycle, so during the out-years of this project we will address the questions: what are the dominant controls on the methane cycle in the 21st century? Will thawing of permafrost and methane clathrates provide a significant positive feedback on high-latitude warming? What are the major biogeochemical consequences of enhanced methane release? We will also examine the impacts of marine and sea-ice ecosystems on the radiative budget through production of chlorophyll and other colored dissolved organic matter (CDOM), and test whether this is a significant contribution to polar amplification.

Coastal Processes

In the current version of CESM, run-off from continents and ice sheets is applied at the ocean surface in prescribed spatial patterns. This ignores the fact that the interactions on the interface between the pelagic and terrestrial domains are immensely complex. Many processes are uniquely important for the coastal ocean, but fully determine the exchanges between the terrestrial and pelagic domains. These processes include wind waves, storm surges, and tides; estuarine circulation and dynamics of deltas; land-fast sea ice; iceberg calving; sediment dynamics like resuspension and aggregation; and a myriad of biogeochemical reactions. Understanding these processes, and how they impact fluvial and glacial inputs into the Arctic and Southern Oceans, requires high spatial resolution, as well as careful consideration and implementation of the relevant processes. Hence, an important part of our 10-year vision is an increased focus on coastal processes in the Arctic and Antarctic; this may be the next frontier of global climate modeling. Among the questions that we will address are: how do deltas and coastal zones modify the exchanges between the continental and pelagic realms? Is freshwater and nutrient transport by icebergs an important control on pelagic ecosystems productivity? Are suspended sediments an important source of nutrients for pelagic ecosystems in the high-latitude oceans? How might changes in permafrost influence riverine outflow (nutrient and water) to coastal regions? What are the dominant (dynamical) controls on cross-shelf exchanges, and how do they depend on shelf geometry and environmental factors? How does land-fast sea ice modulate exchanges between coastal zones and the ocean?

Fully Interactive Ice Sheets

Inclusion of ice sheets within coupled climate modeling frameworks is increasingly recognized as a critical step forward in understanding the system response to external climate forcings. Furthermore, the response of ice sheets is critical to the integrative themes of the HiLAT project, which involve exploration of feedbacks between regional high-latitude and global crysopheric and physical/biogeochemical climate components. However, to date, few full-complexity climate models include interactive ice sheets or ice shelves, largely due to non-trivial technical challenges. This deficit has left fundamental scientific questions unanswered. For example, how important are ice sheet/climate feedbacks to future freshwater flux projections? What is the role of ocean variability and change in determining ice-sheet evolution? What will be the contribution of ice sheets to long-term sea-level rise? Pioneering (and ongoing) DOE-led contributions to couple ice sheets into both CESM and ACME have resulted in technical and scientific leadership that poises DOE researchers and model developers to answer these basic questions, in a fully coupled setting, as part of the HiLAT project.

Improved Atmospheric Processes

The atmosphere component used in Years 1-3 limits exploration in a variety of ways that are important for high-latitude climate. The relatively low (horizontal and vertical) resolution used in our first years make it difficult to represent topographic features that are important to the climate in both the Arctic and Antarctic. During Year 4-10 we anticipate ACME atmosphere model improvements (hinted at in the original proposal) to ice and liquid cloud microphysics, atmospheric dynamics, turbulent mountain stresses, aerosol production-and-loss mechanisms, and an explicit coupling between atmospheric processes and the “elevation class” decomposition being developed in the land model (and ice-sheet model). These improvements should help in producing much more realistic simulations of meteorological features like blocking events, precipitation frequency and intensity, katabatic winds, cloud features, and aerosol transport and deposition processes that we know to be relevant to seasonal sea-ice evolution and high-latitude climate extremes. These improvements also influence the surface hydrology relevant to river outflow and ice sheet surface mass balances, so one can begin to explore questions like: how important are realistic regional and seasonal snowpack to river flow in the Arctic, and what impact does that have on Arctic ecosystems? Regionally refined atmospheric models, with high-resolution foci over the Arctic and Antarctic, perhaps nudged by lower-resolution models or weather forecast reanalysis products, also provide the opportunity to explore the integrative regional theme 1 interactions at much lower computational costs. The opportunity to work at both global high (order 25 km horizontal) and low (100 km) horizontal resolution allows us to ask: how much resolution is needed to capture certain meteorological features (e.g., blocking events, precipitation intensity), and what climate features are critical for accurately capturing processes important for particular polar/extra-polar interactions (e.g., extreme weather in the northeast United States)?

The questions we have introduced here are a sample of science we anticipate being able to address, but specific hypotheses associated with these will be selected at the next triennial SFA review, based on current status and availability of the required model developments.

Synergy with Other Projects

The science questions presented above generally require significant model developments anticipated from two important collaborations: the ACME and RASM projects. The figure shows a schematic roadmap for how these developments will be integrated to advance HiLAT science and provide continued collaboration in improving polar simulations.

ACME

ACME is a major DOE global climate model development initiative started last year that will implement significant new capabilities during the next 3 to 10 years, many of which are relevant to polar climate. Beginning in Year 3 of the HiLAT project, we plan to capitalize on the major new model capabilities that are currently under development within ACME. There is significant overlap of personnel between the

HiLAT and ACME projects, which will ensure that we stay abreast of ACME developments and facilitate our rapid adoption of new ACME capabilities as they become available.

A number of ACME developments will be particularly important for future HiLAT science. Among these are 1) regionally refined model grids in both atmosphere and ocean; 2) higher vertical resolution and a raised model top in the atmosphere model; 3) improved treatments of clouds and aerosols; 4) improved land BGC capabilities and elevation classes for better topographic resolution; 5) improved “bi-polar” sea ice biogeochemistry; and 6) further advances to ice-sheet modeling, particularly to integrate marine-based ice sheets into a coupled framework. Resolution improvements are critical to provide the capability to capture ocean eddies, atmospheric processes, and coastal interactions. Regionally refined grids are a particular target for creating regional Arctic and Antarctic models with global extent. New BGC improvements will enable us to address methane, new aerosol interactions, and other species. Fully interactive ice sheets, including Antarctic marine ice shelves, and land elevation classes will permit further work toward quantifying future sea-level rise.

RASM

In addition to the relationship with ACME, we will continue and strengthen our collaboration with the RASM project. During years 1-3 of HiLAT, we will pursue complementary simulations using our current model configurations (CESM and RASM). In particular, RASM will be pursuing high-resolution regional Arctic simulations to complement our longer-term coarse-resolution ensembles. However, joint work on CICE coupling issues and biogeochemistry will provide opportunities for continued collaboration in configuring and applying our models for shared science goals. We will also collaborate on joint analysis and metrics development. After year 3, both the HiLAT and RASM projects anticipate adopting the ACME v1 model with its new capability to use regionally refined grids. HiLAT and RASM will collaborate to create an Arctic regional model at high resolution while retaining global extent at coarser resolution. At that time, HiLAT and ACME will be sharing the ACME code base and will further collaborate on a number of Arctic science questions, especially in future sea ice behavior and Arctic ocean circulation changes.

Regional Arctic System Model (RASM)

U.S. DEPARTMENT OF ENERGY | Office of Science

REGIONAL ARCTIC SYSTEM MODEL (RASM)

The core effort of this project involves the development and use of a Regional Arctic System Model (RASM), consisting of atmosphere, land, ocean and sea ice, as well as vegetation, Greenland Ice Sheet, ice caps and smaller glaciers. A major goal of the research is to produce a more realistic and detailed picture of the climate patterns, which are emerging in the region, as well as to provide a greater insight into what processes and feedbacks future Global Climate and Earth System Models should improve upon.

This project grew out of regional Arctic climate modeling work at the Naval Postgraduate School, the University of Colorado, Iowa State University, and the University of Washington. Currently, our team involves 30 researchers, including students, from 10 institutions. Members from each institution have worked with standalone model components, such as ocean, ice, atmosphere and land models, and saw the need for a fully coupled regional climate model that thoroughly explores the interactions between components.

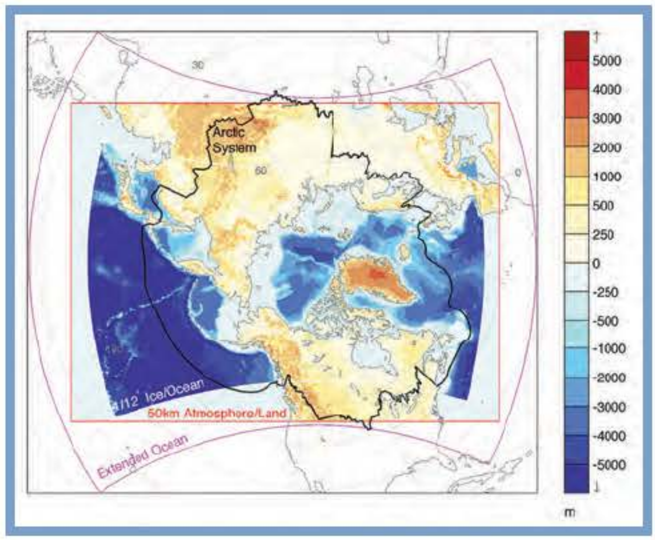
LONG-TERM GOALS

Our long-term goal is to advance knowledge, reduce uncertainty, and improve prediction of Arctic climate through continuous expansion of RASM involving a larger climate community and including ice-sheet/ocean interaction in fjords, terrestrial and marine biogeochemistry, and ecology, and the associated carbon cycle integral to human dimension components. As we continue developing our model and analyzing its results, we gain a greater insight into the basic workings of the climate system.

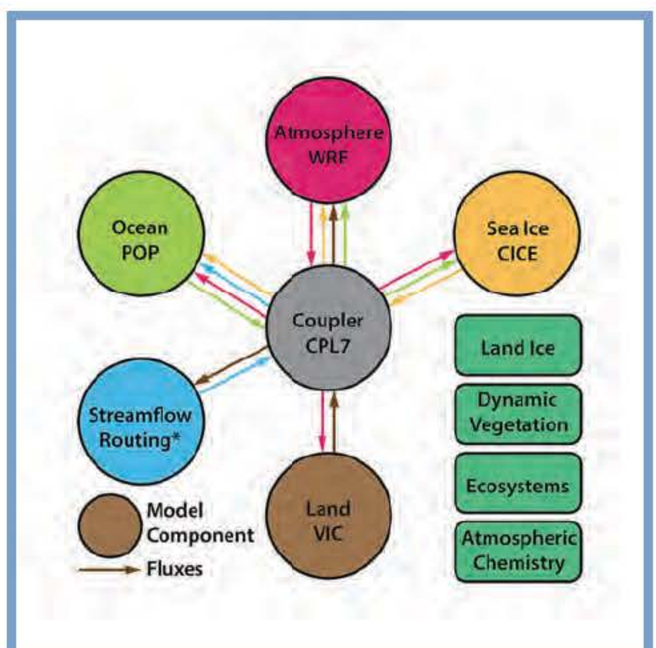
Given that the Arctic is warming faster than the rest of the globe, understanding the processes and feedbacks of this polar amplification is a top priority. In addition, Arctic glaciers and the Greenland Ice Sheet are expected to change significantly and contribute to sea level rise in the coming decades. The aforementioned high-spatial resolution allows for detailed study of the regional response of these land ice masses to long-term warming and interannual variability.

ADVANTAGES

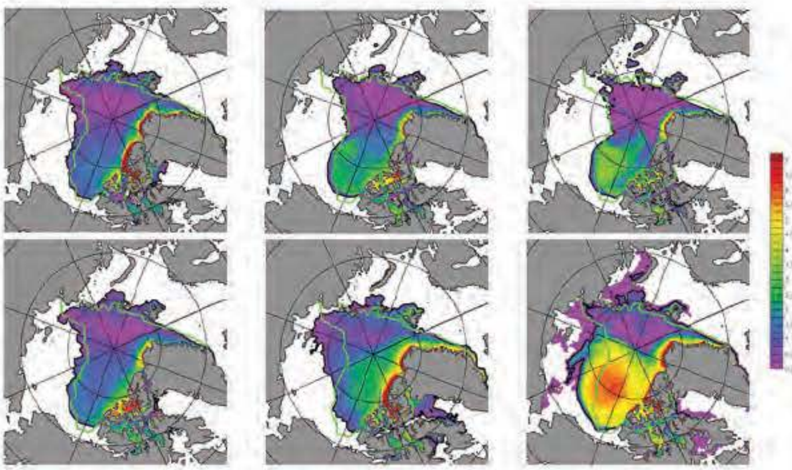
Although similar to Global Climate and Earth System Models, RASM provides two critical advantages. First, given its regional focus, it permits significantly higher spatial resolution to explicitly represent and evaluate the role of important fine-scale Arctic processes and feedbacks, such as sea ice deformation, ocean eddies, and associated ice-ocean boundary layer mixing, multiphase clouds as well as land-atmosphere-ice-ocean interactions. Second, it allows for simulation of a larger number of



Pan-Arctic domains from the Regional Arctic System Model (RASM). Shading indicates model topobathymetry. The black line outlines the Arctic system domain.



Wiring diagram of the Arctic system model.



Sea ice thickness and extent from RASM H-compset sensitivity runs forced with CORE2 for September 2007. The green contour line represents 15% ice concentration from satellite data (NSIDC) with the representative black line from the model. Varying, yet realistic changes in parameter space yield significant variability in sea ice thickness/extent and help determine the optimal setup for RASM.

ensemble members, using different initial conditions and space-dependent sub-grid parameterization, to generate probabilistic predictions that would be more useful to national and local decision makers than global model forecasts alone.

SCIENTIFIC PROGRESS

The first set of results indicates that ice-ocean interactions combined with diminishing sea ice cover plays an important role in the western Arctic Ocean. Over the last decade, there has been a significant depletion of ice pack leading to a rise in subsurface heat content as more of the ocean surface becomes exposed to the sun's rays. Some of this solar energy becomes trapped below the surface layer after freeze-up and can reduce the growth of sea ice in winter, leading to earlier melting/retreat in spring and a further reduction of the Arctic sea ice cover. Such a positive feedback would act in addition to ice-albedo feedback and further contribute to polar amplification.

On the Atlantic side of the Arctic, in the Barents Sea, oceanic heat transport and air-sea fluxes may help explain some of the Global Climate and Earth System Models biases related to the regional atmospheric circulation and excessive sea ice melting in the eastern Arctic. The former appears to be caused by insufficient mixing and cooling of Atlantic water over the Barents Sea. This could help explain the large, positive sea level pressure bias centered over the Barents Sea experienced in many of the Global Climate Models of the World Climate Research Programme's (WCRP) third Coupled Model Intercomparison Project (CMIP3). A more accurate model simulation of water vertical mixing and cooling in the Barents Sea will require improved representation of oceanic currents, eddies, tides, marginal ice zones, and of overall bottom bathymetry.

Further, a depletion of sea ice may have a positive feedback effect on summer weather forecasting because larger areas of direct ocean-atmosphere interaction increase oceanic regulation of the atmosphere (areas, such as Alaska, have shown an increase in warm extremes and a decrease in cold extremes). The warmer weather is likely due to a change in atmospheric circulation influenced by an increase in open ocean area. RASM has also indicated an increase in precipitation in Alaska and Canada, suggesting in the future RASM can be used for exploring precipitation extremes, as well as its many other applications.

Overall, RASM is in good agreement with satellite observations for sea ice variability. More importantly, RASM can realistically represent extreme sea ice events, such as the September 2007 minimum, when forced with realistic atmospheric data from the Common Ocean Reference Experiment version 2 (CORE-2). Since the Arctic sea ice is highly sensitive to and dependent on combined forcing from the atmosphere and ocean, such results bring confidence in the model's ability to simulate processes and interactions affecting the region's surface climate.

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Regional Arctic System Model Current Situation

The Arctic is a complex and integral part of the Earth system, influencing the global surface energy and moisture budgets, atmospheric and oceanic circulations, and geosphere-biosphere feedbacks. Its past-century records exhibit strong variability up to multi-decadal timescales (e.g., Francis et al. 2009, Matthes et al. 2009), which likely results from the combined effects of natural variability and global warming (e.g., Serreze et al. 2009). However, model-based assessments of anthropogenic change in the Arctic are challenging and incomplete without the determination of its background natural variability (Vinnikov et al. 1999, Moritz and Bitz 2000, Holland et al. 2008). Prediction of decadal changes requires understanding, realistically simulating, and coupling the individual Arctic system components, which could be responding at different timescales to anthropogenic forcing.

Historical reconstructions of Arctic climate change from global climate and earth system models (GC/ESMs) are in broad agreement with rapid climatic changes in the high north; however, the rate of change in the GC/ESM forecasts remains outpaced by observations (Stroeve et al. 2012). Those changes include the retreat of the perennial sea ice cover and spring snow extent, warming air and ocean, accelerated ice-sheet outflow, and freshwater runoff and coastal erosion associated with thawing permafrost. Those are some of the most coordinated changes currently occurring anywhere on Earth, with arctic sea ice cover changes exceptional in at least the last 1400 years and related surface temperature extremes unusual in at least the past 600 years.

There are a number of reasons why GC/ESMs may not be able to simulate rapid environmental change in the Arctic, including: i) poorly resolved clouds and cloud processes impacting net surface radiation, ii) shortcomings in boundary layer and bulk surface flux parameterizations, iii) unresolved oceanic currents, eddies, and tides that affect the advection of heat into and around the Arctic Ocean, iv) crudely represented sea ice mechanics, surface snow processes, sea ice melt ponds, and surface roughness that affect ocean-ice-atmosphere surface momentum and energy transfer, and v) poorly resolved land surface processes such as albedo effects of snow/vegetation interactions, permafrost and active layer development, the evolution of seasonal meltwater lakes and wetlands, and the accumulation and melt of mountain glaciers and snow fields, all of which affect the freshwater flux to the Arctic Ocean and the energy and momentum exchange between the land and atmosphere. These shortcomings stem from a combination of coarse model resolution, inadequate parameterizations, unrepresented processes, and a limited knowledge of physical, real-world interactions.

Resources

Such processes and related feedbacks as mentioned above directly control regional Arctic climate variability and indirectly exert control on global climate variability. The need for their realistic representation is motivating development of models with very high spatiotemporal resolution and new parameterizations. This, in turn, is stimulating more robust model evaluation against long-term observations in the Arctic that represent scales that were until recently unresolved by even the highest-resolution models. However, a system-level understanding of critical Arctic processes and feedbacks is still lacking, in part because the scientific community's understanding of polar phenomena is still limited by chronic under-sampling. For this reason, high-resolution, limited-area models of the Arctic are increasingly being adopted as a way to downscale coarse-resolution, observation-based reanalyses and to better understand coupled high-resolution processes and feedbacks.

A number of authors have stressed the need for high-fidelity regional ensemble projections to generate probabilistic predictions that would be more useful to national and local decision-makers than global model forecasts alone (Giorgi 1995, Challinor et al. 2009, Doherty et al. 2009, Moss et al. 2010). This is especially germane for the Arctic, where economic, social, and national interests are rapidly reshaping the High North in step with regional climate change. Regional models offer exceptional spatio-temporal coverage and an insight into processes and feedbacks typically not resolved in GC/ESMs. Regional simulations facilitate detailed seasonal comparisons with observations that are not possible using global simulations. Due to the additional constraints (from lateral boundary conditions and nudging within a regional model domain) imposed on regional, compared to global, simulations, output from regional models may be compared with month-on-month observational statistics, with equitable model and observation variance stemming from similarly resolved scales. As such, regional climate models form part of a model hierarchy important for improving climate predictions: from simple, 1D process-based models, to regionally constrained simulations, and ultimately to fully coupled Earth system codes (Knutti 2008). This hierarchy assists in the development of 'unified models' that represent energy cascades from fine-scale processes to the planetary-climate scale (Hurrell et al. 2009; Brown et al. 2012).

Quantifying the relationship between skill and uncertainty (i.e., variance of different model realizations) in polar climate projections has become a major goal of arctic modeling. Such a relationship is neither straightforward nor well understood because GC/ESMs are becoming increasingly complex and isolating polar causation from polar feedbacks in fully coupled simulations is challenging. Regional Arctic models can assist in this task, because they limit the spatio-temporal domain of the active system to help separate external forcing from internal Arctic System response. They also facilitate the addition or removal of parameterized and resolved processes to identify contributors to variability and change in the regional system. Moreover, they can be used to produce multiple realizations, or ensemble members, to help identify sensitivity and determine uncertainty from a single external boundary condition. This ability to regionally isolate signals and test different model resolutions and parameterizations within a limited domain has already been successfully tested (Déqué et al. 2005; Giorgi et al. 2008). We intend to apply some of these approaches to the Arctic and to fully coupled simulations to better understand the relationship between uncertainty and skill in the High North.

We hypothesize that regional coupled models employing resolution sufficiently high to resolve mesoscale processes of importance to individual climate model components and to sensitive, coupled surface feedbacks will add significant value and greater cryospheric and climate sensitivity to seasonal projections than GC/ESMs. We argue that high resolution is a necessary condition for Arctic simulations to account for coupled processes and feedbacks known to affect both mean and extreme behavior. We suggest that this approach will permit extreme values and background high wavenumber and high-frequency noise that contribute to the energy cascades at climatic timescales, which will better characterize uncertainty and improve skill in models.

Near-Term Goals (3-5 years)

The Regional Arctic System Model is a limited-area, fully coupled, ice-ocean-atmosphere-land model (Maslowski et al. 2012). It includes the Weather Research and Forecasting (WRF) atmospheric model, the LANL Parallel Ocean Program (POP) and Community Ice Model (CICE), and the Variable Infiltration Capacity (VIC) land hydrology model configured for the pan-Arctic region. The purpose of the Regional Arctic System Model (RASM) project is to gain a better understanding of the impact of mesoscale processes and resulting feedbacks on seasonal to decadal predictability of the Arctic and their importance in downscaling global simulations, using a domain sufficiently expansive to capture the Arctic as a complex adaptive system.

During this phase of our research, we intend to focus on matching Arctic surface climate sensitivity to particular processes and space-dependent parameters and identifying spatio-temporal changes in these relationships using a hierarchy of regional and global models at varying configurations and observationally based metrics. By surface climate, we mean the state of the system in the atmosphere-ice-ocean boundary layer system and at the land interface. In addition, we will also examine mass, heat, moisture, and salt/freshwater convergence to and their budget within the Arctic. The proposed research will advance understanding of physical processes and their feedbacks of relevance to Arctic climate with the goal of improving simulations of the past, present, and future Arctic climate change. This will be achieved using latest-generation regional and global earth system models (ESMs) implemented across a spectrum of spatio-temporal resolutions. Our research aims to initially use a regional model (RASM) and a global model (CESM) to evaluate their skill in representing past and present climate variability against observationally derived metrics. We will use two regional model configurations of (RASM - 50/25 km atmosphere-land and 1/12º / 1/48º ice-ocean) and two global model configurations of the Community Earth System Model (CESM) (1º atmosphere-land with a nominal 1o displaced pole ice-ocean grid using the gx1v6 ocean mask and 0.5º atmosphere-land coupled to 0.1º ice-ocean). We will run RASM and CESM both fully coupled and with data atmosphere/land models using Common Ocean Reference Experiment inter-annually varying forcing version 2 (CORE-2).

Within the confines of our work with RASM and CESM, we will: i) quantify the added value of using regional models for downscaling arctic simulations from global models, ii) address the impacts of high-resolution, improved-process representations and coupling between model components on predictions at seasonal to decadal time scales, iii) identify the most important processes essential for inclusion in future high resolution GC/ESMs, e.g., Accelerated Climate Modeling for Energy (ACME), using CESM as a test bed, and iv) better quantify the relationship between skill and uncertainty in the Arctic Region for high fidelity models. This work will be conducted in parallel with ACME development at Los Alamos National Laboratory (LANL) and other DOE laboratories. Beneficial RASM modeling techniques, metrics, and analysis methods stemming from our work as well as our expertise gained in this project will be shared as part of ongoing collaboration with LANL to aid development of the DOE ACME to improve simulation for the polar regions.

Mid-Term Goals (10 years)

Fine-resolution global climate configurations have been developed and tested (e.g., McClean et al. 2011), and they provide evidence that refining the spatial resolution of climate models improves the fidelity of their simulations. However, the computational cost of running such ambitious applications is expected to continue to restrict their use in the near to mid-term future. The computational cost will also limit progress with model improvements related to new space-dependent parameterizations, ensemble prediction, and limits of predictability. All this is especially true in the Arctic, where the finest possible spatial resolution is needed. Therefore, the development and use of high-resolution regional Arctic climate and system models and process-level subsystem models are important stepping stones in the coming decade for dedicated studies of regional processes and feedbacks, tests of new parameterizations and ensemble simulations, and the prediction of sea ice and other components of the

Arctic System in a warming climate. Careful assessment of the additional benefits of increasing model resolution and/or complexity, such as offered by RASM, will be important to guide future investments in model development.

Another opportunity for advancing Arctic system modeling is underway with the development of a variable-resolution or unstructured grid approach (e.g., Ringler et al. 2010) within the DOE ACME project that shows great promise for bridging the gap and enabling high-resolution regional Arctic climate change exploration within the context of the global climate system model framework. Subject to further progress with ACME development and access to its codes by the university community, including the RASM team, an improved framework for robust regional Arctic climate system modeling might become available soon.

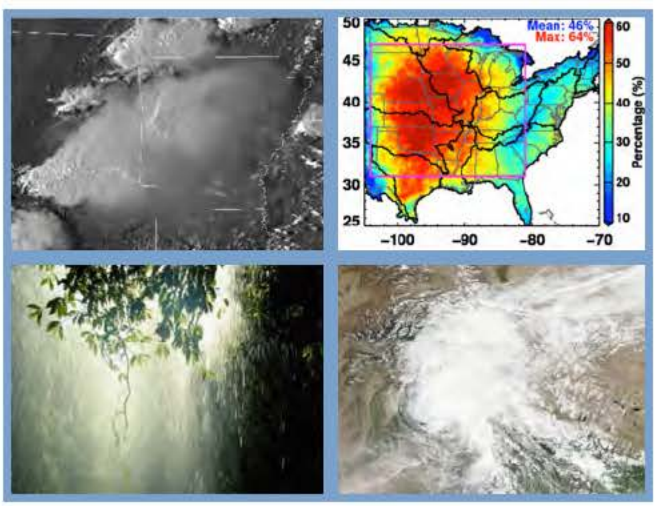
The mid-term goal motivating RASM project is to capitalize on the PIs' joint expertise in building and using a new high-resolution, fully coupled model for the pan-Arctic region (i.e., RASM) to: i) facilitate construction of multi-model Arctic test-bed tool, ii) contribute to the advancement of new sea ice and ocean model components within the framework of the LANL Model for Prediction across Scales (MPAS-CICE and MPAS-Ocean) by offering innovative model evaluation methods for the task (e.g., a MATLAB Toolbox named "Icepack" or a satellite emulator) , and iii) aid development, use, and evaluation of the next generation of global earth system models by the Department of Energy.

Finally, in addition to Arctic climate research, another RASM mid-term goal is to leverage the ongoing work within the complementary ice-ocean or marine biogeochemistry project (RASM-mBGC), recently funded by NSF in collaboration with LANL. Our goal is to advance research on and predictive capability of the Arctic carbon cycle under warming climate, of relevance to the DOE Office of Science Biological and Environmental Research Program.

Water Cycle and Climate Extremes Modeling (WACCEM)

WATER CYCLE AND CLIMATE EXTREMES MODELING

Since the dawn of the industrial era, human activities have significantly perturbed the climate system and water cycle, with serious consequences for human society and ecosystems. Achieving robust prediction of water cycle changes in the future has been challenging because large-scale circulations have dominant control on regional precipitation, but the dynamical and thermodynamical processes that govern large-scale circulation changes are not well understood. For example, while progress has been made in documenting and understanding the robust changes in the zonally symmetric component of the general circulation, the global warming signal associated with the zonally asymmetric circulation, such as the monsoon, is still unclear. Latent heat release associated with convection is a key driver of large-scale circulation. However, representing convection has been one of the foremost challenges in climate modeling. Limitations in modeling convection have implications not only for depicting large-scale circulation features through multiscale convection-circulation interactions, but mesoscale-organized convection is a ubiquitous mechanism responsible for heavy rainfall and flooding worldwide. By improving understanding and modeling of water cycle processes, this project addresses the strategic goal of the U.S. Department of Energy's Climate and Environmental Sciences Division to "advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges."



As mesoscale convective systems account for up to 64% of warm-season precipitation in the U.S. Great Plains (top panels) and frequent many regions including the Amazon basin and Indian sub-continent (bottom panels), they play an important role in the hydrological cycle worldwide. With most climate models failing to capture these organized convective storms, the consequential biases in the latent heating in the atmosphere, surface energy, and water balances have important implications to simulating large-scale circulation, land-atmosphere interactions, and regional precipitation response to global warming.

SCIENCE OBJECTIVES

The 10-year vision of the Water Cycle and Climate Extremes Modeling (WACCEM) project is to tackle the above challenges to advance robust predictive understanding of water cycle processes and associated

KEY QUESTIONS FOR FY 2016-18:

- What are the governing mechanisms of monsoon systems and their impact on the zonally asymmetric circulation, and how will they change in response to climate warming?
- What are the dynamical linkages between the jet stream and wave breaking with atmospheric rivers and their moisture transport, and what are the implications of changes in these circulation features for extreme precipitation in the extratropics?
- What are the relative impacts of atmosphere and land-surface conditions on convection in the central U.S. and Amazon?
- How may the structure of mesoscale convective systems change in a warmer climate and impact extreme precipitation?
- What are the roles of diabatic processes, particularly associated with convection and aerosols, in the Asian monsoon system and their responses to future warming?
- What are the climatological relationships between the South Asian monsoon and North Indian Ocean tropical cyclones, and how may these relationships change in a warmer climate and affect precipitation?

extremes and their changes in a warming climate. It will address three overarching science questions:

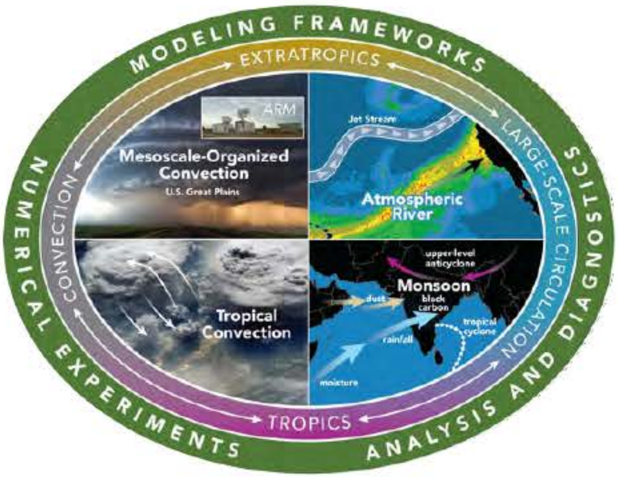
1. How do large-scale circulation features, such as the extratropical storm tracks and monsoon systems, modulate regional mean and extreme precipitation, and how will they change in the future?
2. What processes control mesoscale-organized convection and associated warm-season regional mean and extreme precipitation, and how will they change in a warmer climate?
3. What are the robust multiscale connections between atmospheric circulation features and water cycle processes, and how do they influence regional precipitation?

RESEARCH FOCUS

WACCEM is organized into four major elements for fiscal years (FY) 2016-18. Research Element 1 advances modeling frameworks, performs a hierarchy of numerical experiments, and develops diagnostic/analysis methods. Research Elements 2 through 4 probe the mechanisms and processes underlying each science question.

Research Element 1: Modeling Frameworks, Analysis and Diagnostics, and Numerical Experiments

The main objective is to advance a global multi-resolution modeling framework based on the non-hydrostatic Model for Prediction Across Scales (MPAS) coupled with the Community Atmosphere Model physics for simulations down to convection-permitting resolution. A suite of diagnostics and analysis methods will be developed to address the science questions targeted by Research Elements 2 through 4.



The objectives of WACCEM will be advanced through research in four elements: (1) Modeling frameworks, analysis and diagnostics, and numerical experiments; (2) Large-scale circulation (monsoon and atmospheric river); (3) Convection (U.S. Great Plains and Amazon); and (4) Multiscale monsoon-convection interactions (Asia).

Research Element 2: Large-scale Circulation

This element targets two important large-scale circulation features—monsoon systems and atmospheric rivers—with important implications for regional precipitation and extremes. Building an idealized modeling hierarchy, a first-order picture and governing principles of the monsoon will be developed. By linking atmospheric rivers to the jet stream and wave breaking, and using observations from the CalWater 2 and ACAPEX (ARM Cloud Aerosol Precipitation Experiment) field campaign, the moisture sources and transport pathways of atmospheric rivers will be quantified.

Research Element 3: Convection

This element evaluates the relative impacts of atmospheric and land-surface conditions on convection and investigates potential changes of the structure of mesoscale convective systems in a warmer climate and the implications to extreme precipitation. Model simulations will be evaluated using observations from the Atmospheric Radiation Measurement (ARM) Climate Research Facility at the Southern Great Plains and the GoAmazon 2014/2015 field campaign.

Research Element 4: Multiscale Monsoon-Convection Interactions

This element investigates the roles of diabatic processes in the Asian monsoon and their responses to global warming. Moisture budget analysis will be used to attribute specific diabatic heating fields associated with the Asian monsoon divergent circulation and moisture transport. Numerical experiments will investigate changes in monsoon precipitation and tropical cyclone activity in response to greenhouse gases and absorbing aerosols.

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10-Year Vision

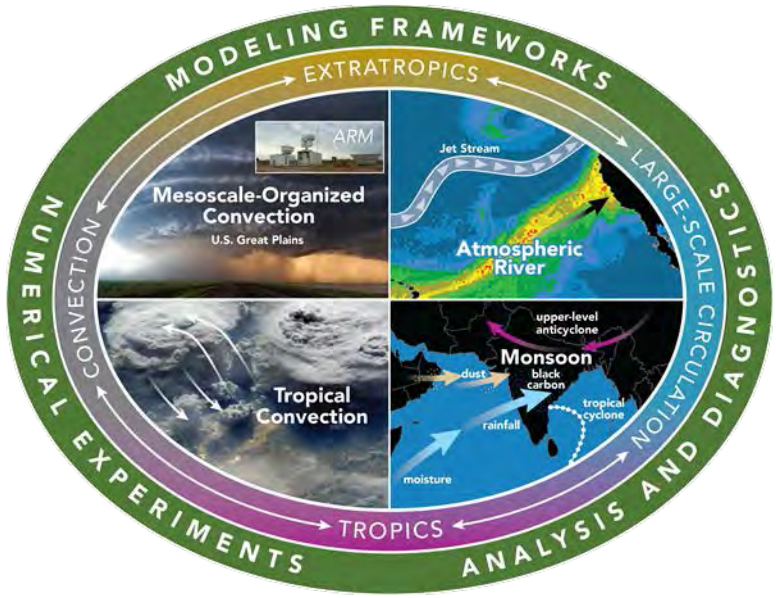
The WACCEM SFA has identified three science grand challenges that limit our ability for robust prediction of water-cycle changes in the future: First, large-scale circulations have dominant control on regional precipitation, but the dynamical and thermodynamical processes that govern large-scale circulation changes are not well understood. Second, mesoscale-organized convection plays a crucial role in producing heavy precipitation and floods, but representing convection has been one of the foremost challenges in climate modeling. Third, there are significant interactions between atmospheric circulation and water through multiscale processes, particularly associated with moist convection and its diabatic heating. Understanding and reducing uncertainties in how models represent these processes are essential to constrain model projections of water-cycle and climate extremes in the future. Our 10-year vision is to tackle these challenges to advance robust predictive understanding of water-cycle processes, especially hydrologic extremes, and their changes in a warming climate.

3-5 Year Vision and Actionable Items

In the next 3-5 years, we will address three overarching science questions and a subset of key questions:

- How do large-scale circulation features, such as the extratropical storm tracks and monsoon systems, modulate regional mean and extreme precipitation, and how will they change in the future? Actionable items or research tasks include:
    - Investigate the governing mechanisms of monsoon systems, and their impact on the zonally asymmetric circulation, and how they will change in response to climate warming.
    - Explore the dynamical linkages between the jet stream and wave breaking with atmospheric rivers and their moisture transport, and understand the implications of changes in these circulation features for extreme precipitation in the extra-tropics.
- What processes control mesoscale-organized convection and associated warm-season regional mean and extreme precipitation and how will they change in a warmer climate? Actionable items or research tasks include:
    - Determine the relative impacts of atmosphere and land-surface conditions on convection in the central United States and Amazon.
    - Study how the structure of mesoscale convective systems may change in a warmer climate and impact extreme precipitation.
- What are the robust multiscale connections between atmospheric circulation features and water-cycle processes, and how do they influence regional precipitation? Actionable items or research tasks include:
    - Determine the roles of diabatic processes, particularly associated with convection and aerosols, in the Asian monsoon system and their responses to future warming.
    - Examine the climatological relationships between the South Asian monsoon and North Indian Ocean tropical cyclones, and how these relationships may change in a warmer climate and affect precipitation.

These research areas are summarized in the schematic below.



Core Scientific and Technical Capabilities

The WACCEM research will deliver new understanding of mechanisms of water-cycle changes in the future and sources of uncertainty in climate model projections of future changes. This research will:

- Advance new understanding of the fundamental mechanisms of monsoons.
- Quantify the moisture sources and pathways of atmospheric rivers and their linkages to the jet streams.
- Evaluate the relative roles of atmosphere and land-surface control on mesoscale-organized convection and the response of convection to warming.
- Elucidate the multiscale interactions between monsoon and convection, the impacts of GHG and aerosols on the South Asian monsoon, and connections of the latter with tropical cyclones in the North Indian Ocean.
- Reveal and quantify the sources of uncertainties in model projections of changes in the aforementioned processes, which are all intimately linked to precipitation at multiple time and space scales.

Facilitated by the DOE high-performance computing resources and unique observations (e.g., ARM Southern Great Plains [SGP] and Green Ocean Amazon [GoAmazon] 2014/15), the WACCEM research will demonstrate new modeling framework, diagnostic and analysis tools, and data sets:

- Demonstrate and evaluate a non-hydrostatic, multi-resolution global modeling framework for climate simulations down to convection-permitting scale.
- Evaluate and advance the use of ACME for water-cycle research.
- Generate and archive model outputs from a hierarchy of idealized and real-world numerical experiments and data sets (e.g., synthesized observations from CalWater2-ACAPEX and OLYMPEX for atmospheric river cases).

- Develop and archive synthesized GoAmazon 2014/15 and SGP observations for convection study; long-term MCS database for the United States) and made available to enable research by the broader community.
- Implement diagnostic/analysis methods in computer code and document them in the literatures.

The WACCEM SFA consists of integrated research elements requiring sustained and significant efforts to address science grand challenges that cannot be tackled by individual university teams.

Gaps

WACCEM research can be enhanced by and synergistic with the following:

- ASR research on process understanding of convection and land-atmosphere interactions.
- ASR research on parameterization improvements of cloud and convection processes.
- ARM and ESS observation data on convection, land-surface processes, and land-atmosphere interactions for analysis of processes and model evaluation.
- SciDAC Multiscale Modeling on scale-aware parameterizations that can be used in global variable-resolution models.
- Other RGCM projects on development and computational efficiency of methods and tools to analyze and diagnose climate model behaviors (e.g., CASCADE, PCMDI, NCAR project, university projects on climate extremes).
- ACME coupled modeling capability and simulations for understanding water-cycle processes in the fully coupled Earth system.
- ASCR capabilities to improve computational efficiency of MPAS.
- Contribution to and analysis of CMIP6 simulations to facilitate understanding of uncertainty in multi-model ensemble.
- Synergistic simulations to generate a more systematic hierarchy of simulations to understand model uncertainty and guide future model development.

Calibrated And Systematic Characterization, Attribution, and Detection of Extremes (CASCADE)

CALIBRATED AND SYSTEMATIC CHARACTERIZATION, ATTRIBUTION, AND DETECTION OF EXTREMES

Changes in the risk of extreme weather events may pose some of the greatest hazards to society and environment as the climate system changes due to anthropogenic (i.e., human-caused) warming. Extreme weather has recently focused public attention on the dramatic consequences that follow from such events. In 2011, unusually high precipitation, combined with high snowpack, caused extensive flooding throughout the central United States. In 2012, a heat wave across the same region produced the country's hottest year on record, and Superstorm Sandy caused severe storm surges along the Eastern seaboard. The year 2013 brought intense downpours and subsequent flooding across Colorado's front range, causing equally unprecedented damage.

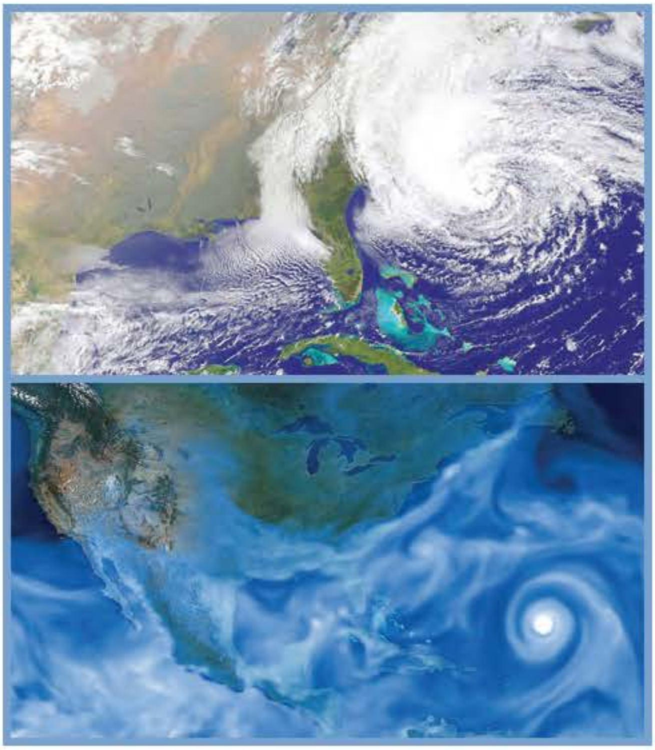
If the severity of extreme climate events continues to increase, this would constitute one of the most stressing forms of climate change for both society and the environment. Therefore, it is crucial to predict with greater reliability how extreme events might change in the future and, in order to advance this objective, to determine with as much certainty as possible whether and why extreme events have already changed.

SCIENTIFIC FOCUS

The intersection of climatic extremes with critical water and energy resources for the United States is emerging as a key focal area for climate research in the U.S. Department of Energy (DOE). This priority is reflected in the DOE *Climate and Environmental Sciences Division Strategic Plan*, the 2012 *DOE Workshop on Community Modeling and Long-Term Predictions of the Integrated Water Cycle*, and a 2013 DOE report on *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather*. Sponsored by the DOE's Regional and Global Climate Modeling program, the Calibrated and Systematic Characterization, Attribution, and Detection of Extremes (CASCADE) project addresses the critical knowledge gaps on climate extremes needed to advance DOE's mission.

CASCADE is developing the following capabilities to accelerate DOE's research portfolio in climate extremes and to advance scientific capabilities in climate analysis:

1. Characterization, detection, and attribution of simulated and observed extremes
2. Development of analytic methodology to characterize extreme events

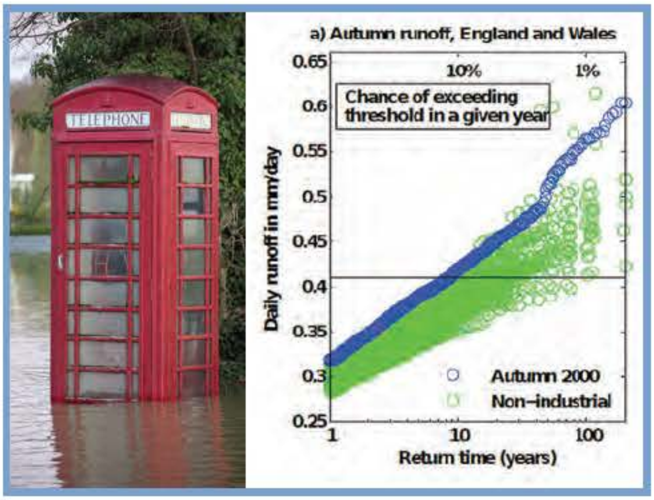


CASCADE is investigating whether and how current hurricanes are affected by global climate change and how these effects will be amplified by future climate change. At the top is a satellite image of Superstorm Sandy while at the bottom is a simulation of a typical Atlantic hurricane.

3. Evaluation and improvement of model fidelity in simulating extremes
4. High performance software to support petascale analysis of extreme events

These capabilities will be used to answer several key science questions:

1. Has the nature of extreme events changed in recent history (e.g., the frequency, duration, intensity, and spatial extent)?
2. If so, what has contributed to this change?
3. How might the nature of extreme events change in the future?



Extreme weather events, such as the Autumn 2000 United Kingdom flood (left), are used to develop simulations of similar flooding events (right) by comparing observed conditions (blue) with simulations omitting anthropogenic greenhouse warming (green).

OBJECTIVES

Characterization, detection, and attribution of simulated and observed extremes

CASCADE will compile observed extreme statistics, calculate probabilities of single and coincident extremes due to anthropogenic influence, and project future changes in the risks of these extreme events. In terms of project goals, the investigation will have several outcomes: (1) it will advance our understanding of the connections among the scales, intensities, causative factors, and impacts of extremes; (2) it will develop new frameworks to quantify the fidelity of simulated extremes using multi-model hindcasts, near-term forecasts, and perturbed-physics ensembles; and (3) it will apply this information to determine the uncertainties in simulated future trends in extremes from the Community Earth System Model (CESM) model system.

Development of analytic methodology to characterize extreme events

CASCADE will utilize advanced statistical methods and uncertainty quantification as integral elements of the project. The impacts of these methods will be to (1) allow the study of extreme events in their full complexity by building climatological expertise directly into the analysis of extreme events through the use of pattern detection methods, combined with extreme value methods; (2) allow the use of near-term predictions as a climate model diagnostic tool; and (3) provide a better understanding of uncertainty in both trends of extreme events and attribution of changes in extreme events to anthropogenic forcing.

Evaluation and improvement of model fidelity in simulating extremes

CASCADE aims to produce a climate model whose ability to simulate extreme events changes in well-defined and predictable ways as the model configuration changes. This work will have three main impacts: (1) it will produce a comprehensive evaluation of the CESM's ability to simulate extreme events; (2) it will reduce uncertainty associated with sensitivity of model results to model configuration: and (3) it will improve the overall model fidelity in its treatment of the relevant physical processes.

High performance software to support petascale analysis of extreme events

CASCADE will create a compact software architecture, leveraging a large amount of community support that can be easily extended by climate scientists worldwide. The effort is designed to produce several significant new capabilities for climate science: (1) development of high-throughput pipelines to determine structural, dynamic, initial-condition, and resolution-related uncertainties in model simulations; (2) creation of flexible and extensible linkages among widely-used statistical, analytical, and graphic tools for end-to-end workflows; (3) extension of uncertainty quantification tools to treat a wide of variety of extreme phenomena; and (4) unrestricted provision of the resulting toolkit to the international climate community.

COLLABORATIONS

The CASCADE project is multidivisional, collaborative work at Lawrence Berkeley National Laboratory (LBNL), drawing upon expertise of scientists in the lab's Computational Research Division and Earth Sciences Division as well as the University of California, Berkeley, and University of California, Davis, campuses. CASCADE scientists collaborate with related projects at LBNL. These projects include a large-scale simulation of climate extreme statistics in recent past and near-term future timescales and a multi-institutional investigation of multiscale processes in the climate system. The resulting connections and related projects will ensure tight integration of observations, experiments, and modeling of extreme climate events.

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Calibrated and Systematic Characterization, Attribution, and Detection of Extremes
3-, 5-, and 10-Year Plans

Our 10-year vision is to target actionable understanding of:

1. Multi-variate behavior and multi-sectoral impacts of extreme weather events;
2. Physical mechanisms for change in extreme weather events in warmer climates; and
3. Advances in skill in the prediction, detection, and attribution of extremes due to the advent of extreme-scale climate models and data analytics.

To make concrete progress towards this 10-year vision, over the next 3 years our vision is to:

1. Develop multi-variate extreme value theory for rare combinations of coincident physical manifestations of extremes, and apply this theory to characterize past and future extremes with high risk of significant impacts;
2. Understand the instabilities and dynamics of the warmest regions on Earth in the present-day climate, to predict the large-scale changes (in particular regime shifts) as more regions warm; and
3. Commence analysis of extremes in a hierarchy of ultra-high-resolution, regional-to-global models, including LES codes, CRMs, super-parameterized GCMs, and novel adaptive-mesh-resolution atmospheric models.

On a 5-year time scale, we will continue advances towards our 10-year vision by:

1. Researching linkages between the physical manifestations and resulting impacts of single and multiple coincident and/or collocated extremes, e.g., coincident droughts and heat waves;
2. Using the physics and dynamics of the climate system to predict the rates of change in the frequencies and magnitudes of coincident hydrometeorological extremes, especially droughts and heavy storms as storm tracks shift poleward; and
3. Quantify the increased fidelity of simulations of observed extremes using extreme-scale regional and global models, and quantify the changes in risk and impacts of future extremes using these next-generation tools.

Multi-Variate Behavior and Multi-Sectoral Impacts of Extreme Weather Events

Climate extremes are considered to be one of the most stressing forms of climate change by the IPCC. The risks to society and the natural environment are magnified when multiple types of extremes are coincident and collocated, e.g., simultaneous droughts and heat waves, downpours and storm surges (e.g., both caused by atmospheric rivers) in coastal zones, and other potentially destructive combinations of extreme weather events. We propose to label these phenomena as compound extremes. At present, however, the theory of extreme values that underpins much of the existing analysis of simulations and observations has been formulated for characterization of univariate phenomena—for example, just drought severity—rather than that of multi-variate phenomena such as coincident droughts and heat waves. Conventional extreme value theory is therefore unsuitable for quantifying the properties—in particular, the magnitudes and return frequencies—of compound extremes. It is also unsuitable for quantifying the increasing risks of multi-sectoral impacts arising from changes in the frequency and severity of compound extremes in a warmer climate.

3-, 5-, and 10-year plan: We will develop the necessary theory for multi-variate extremes that will reduce to the classical Generalized Extreme Value (GEV) theory widely used to study these phenomena in the limit of a single variable. The conceptual breakthroughs and theoretical derivations required are already well underway with university colleagues. The longer-term challenge after the development of the statistical theory is learning how to interpret the multi-dimensional space of extremes in the context of impacts.

Physical Mechanisms for Change in Extreme Weather Events in Warmer Climates

The tropical climate system contains the warmest ocean waters on the planet, the largest organized regions of deep convection (the ITCZ and SPCZ), and the highest values of the water-vapor greenhouse effect. This region is particularly important for climate change, both because other regions as they warm will increase mimic aspects of its process-oriented dynamics, and also because the interactions among radiative-convective instability, convective self-aggregations, cloud feedbacks, and extremes remain to be fully understood. It is still not known whether and by how much convective self-aggregation will amplify the differences between droughts and downpours in the tropics and, soon, sub tropics. It is also not known whether the instability in radiative-convective equilibrium at high sea-surface temperatures could lead to “mode locking” with longer intervals of strong rain followed by little or no appreciable precipitation. Understanding these changes in convection at high temperatures could also be critical for understanding changes in natural variability strongly linked to convection in warmer climates, in particular the Madden-Julian Oscillation and the El Niño Southern Oscillation.

3-, 5-, and 10-year plan: We will use a combination of satellite data, reanalyses, climate models, and process-oriented models to characterize the states, and transitions among these states, of the tropical Pacific and Indian Oceans. We will further develop the theory of instabilities in radiative convective equilibrium, which has potentially significant implications for extremes in the future very warm climates, using a systematic strategy of idealized-to-realistic numerical experiments complemented by a hierarchy of simplified-to-full-complexity models of the relevant physics and coupling to large-scale dynamics. Our goal is to determine whether the warmest climates will manifest a different set of durable or long-lived climatic states that would be associated with impactful regime shifts in rainfall distributions, frequencies, extremes, and accumulations.

Advances in Skill in the Prediction, Detection, and Attribution of Extremes Due to the Advent of Extreme-Scale Climate Models and Data Analytics

Some of the most impactful types of climate extremes are unusually severe hydrometeorological phenomena, e.g., convectively driven downpours, severe storms, tropical and extratropical cyclones, and hurricanes. Our ability to project the changes in these phenomena in warmer climates is predicated on developing and calibrating a physics-based representation of the processes governing these phenomena. However, to date this has been infeasible due to huge disparities between the small length and rapid time scales characteristic of these processes versus the regional to global scales on which climate change operates. This scale disparity, combined with historic limitations on computing power and the long integration times required to simulate global warming, have (to date) prevented physics-based, long-range projections of hydrometeorological extremes. As these projections become increasingly feasible, the challenges associated with conventional methods for analyzing the huge volumes of resulting output will grow literally exponentially, particularly for the high-frequency data required to detect extremes. These challenges will increasingly drive consideration of alternate analytical methods, including "in-line" analysis of extremes while simulations are running followed by post-processing of archived summary statistics.

3-, 5-, and 10-year plan: Over 10 years, we will plan to exploit three major developments in the climate community:

1. The release of the Coupled Model Intercomparison Project (CMIP) v6 (in less than three years), and the likely release of its successor CMIP in connection with the 7th Assessment Report of IPCC;
2. The introduction of extreme-scale supercomputers capable of running ESMs for climate simulations at 10-km resolution (in three years), followed by the deployment of true exascale systems capable of non-hydrostatic and eddy-resolving climate simulations in the next decade; and
3. The advent of ESMs with non-hydrostatic, cloud-system-resolving, atmospheric and eddy-resolving oceanic components combined with concomitant advances in land-surface resolution and hydrological processes.

CASCADE will undertake two major initiatives in response to these activities. First, we will use limited-area cloud-resolving and, where appropriate, large-eddy-simulating models to quantify the impact of increased resolution and process fidelity on our ability to reproduce extremes in the observational record with greater fidelity. As we transition to global cloud- and eddy-resolving ESMs, we will use this information to improve and ideally reduce the uncertainties associated with projected risks of future extremes. Second, we will develop "dual use" implementations of our tools for characterizing extremes that are suitable for massively-parallel analysis of the CMIP archives but that are also adapted for "in-line" application coupled directly to an ESM as it is running. The advantage of the second mode is that the volume of high-frequency data is greatly reduced, thereby accelerating the model performance while vastly reducing the storage resources required to store and post-process huge amounts of model output. This type of "on demand" analytics is already obligatory for other observational physical sciences including accelerator physics and telescopy.

Quantifying Feedbacks and Uncertainties of Biogeochemical Processes in Earth System Models

U.S. DEPARTMENT OF ENERGY | Office of Science

QUANTIFYING FEEDBACKS AND UNCERTAINTIES OF BIOGEOCHEMICAL PROCESSES IN EARTH SYSTEM MODELS

As earth system models (ESMs) become increasingly complex, there is a growing need for comprehensive and multi-faceted evaluation of model predictions. To advance our understanding of biogeochemical processes and their interactions with climate under conditions of increasing atmospheric carbon dioxide (CO_2), we need to develop new ways to use observations to constrain model results and inform model development. Better representation of biogeochemistry–climate feedbacks and ecosystem processes is essential for reducing uncertainties associated with projections of climate change during the remainder of the 21st century.

In an effort sponsored by the U.S. Department of Energy's Office of Science through the Regional and Global Climate Modeling Program, a diverse team from Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, the University of California at Irvine, the University of Michigan, Los Alamos National Laboratory, and Argonne National Laboratory is developing new diagnostic approaches for evaluating ESM biogeochemical process representations. Called the *Biogeochemistry (BGC) Feedbacks Scientific Focus Area (http://www.bgc-feedbacks.org/)*, this research effort supports the *International Land Model Benchmarking (ILAMB) Project (http://www.ilamb.org/)* by creating an open source benchmarking system that leverages a growing collection of laboratory, field, and remote sensing data. This benchmarking system, which will be extended to include ocean biogeochemistry, is expected to contribute model analysis and evaluation capabilities to phase 6 of the *Coupled Model Intercomparison Project (CMIP6)* and future modeling experiments. In addition, the researchers will use this system to engage experimentalists, including those in DOE's Terrestrial Ecosystem Science Program, in identifying model weaknesses and needed measurements and field experiments.

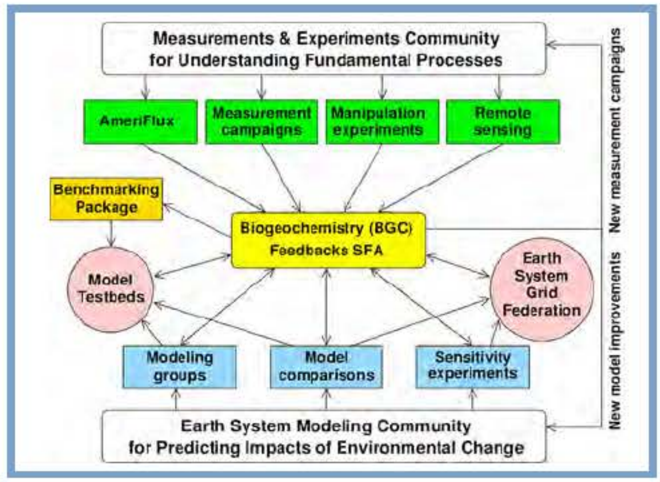

Figure 1: *The Biogeochemistry (BGC) Feedbacks Scientific Focus Area (SFA) brings together the modeling and the measurements communities to systematically assess model fidelity using best available observations through an open source benchmarking package.*

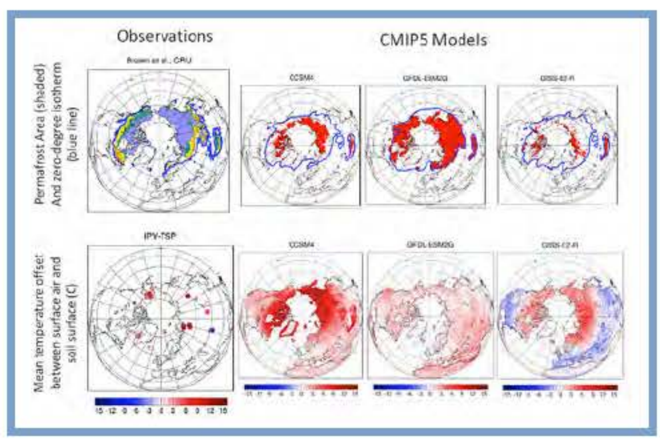

Figure 2: *CMIP5 models exhibit a large inter-model spread in permafrost properties, including permafrost area and mean temperature across the atmosphere-soil interface. However, none of these individual variations was strongly related to modeled permafrost susceptibility to warming. Figure adapted from Koven et al. (2013).*

SCIENTIFIC FOCUS

The overarching goals of this activity are to identify and quantify the feedbacks between biogeochemical cycles and the climate system, and to quantify and reduce the uncertainties in ESMs associated with these feedbacks. Through a comprehensive program of hypothesis-driven research, these goals will be accomplished by performing multi-model sensitivity analyses and comparisons with best-available observations and derived metrics. Investigations will focus on biogeochemistry–climate feedbacks associated with changes on interannual to decadal timescales (including ecological impacts of changes in disturbance regimes and climate extremes) and longer-term trends (including potential tipping points).

Important classes of observations used in the effort include observations of energy, carbon, and water from U.S. Department of Energy Ameriflux and Next Generation Ecosystem Experiments, NASA remote sensing observations of land and ocean ecosystem characteristics, NOAA and NSF atmospheric trace gas observations from aircraft and surface sites, above- and below-ground carbon inventories, atlases of three-dimensional ocean carbon and nutrient distributions compiled from shipboard observations, and syntheses and meta-analyses of terrestrial ecosystem manipulations of carbon dioxide, warming, nutrients, soil moisture, and tree cover.

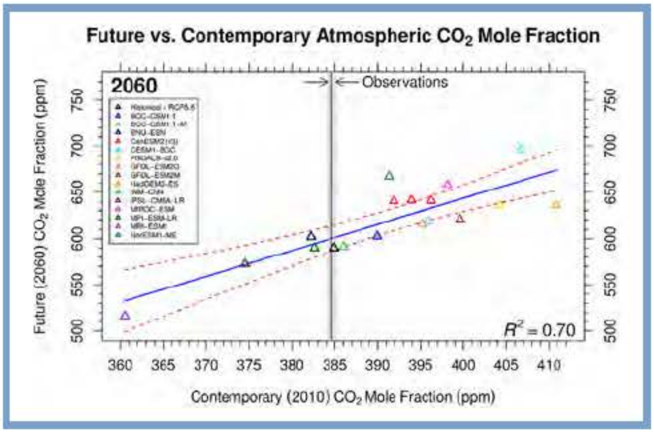

Figure 3: *Future (2060) vs. contemporary (2010) atmospheric CO_2 mole fraction fit for CMIP5 emissions-forced simulations of RCP 8.5. Models that had positive biases in contemporary CO_2 tended to predict higher levels of CO_2 during the middle and end of the 21st century as a consequence of weak carbon–concentration feedbacks. Figure adapted from Hoffman et al. (2014).*

OBJECTIVES

Four objectives define the research focus of this activity:

1. development of new hypothesis-driven approaches for evaluating ESM biogeochemical processes using observations from site, regional, and global scales;
2. investigation of the degree to which contemporary observations can be used to reduce uncertainties in future scenarios, using an "emergent constraint" approach;
3. creation of an open source benchmarking software system that leverages the growing collection of laboratory, field, and remote sensing data sets for systematic evaluation of ESM biogeochemical processes; and
4. evaluation of the performance of biogeochemical processes and feedbacks in different ESMs participating in model intercomparison projects, including CMIP5 and CMIP6.

Another important objective is to contribute to International Land Model Benchmarking (ILAMB) Project by providing new analysis approaches, benchmarking tools, and science leadership. The goal of ILAMB is to assess and improve the performance of land models through international cooperation and to inform the design of new measurement campaigns and field studies to reduce uncertainties associated with key biogeochemical processes and feedbacks. ILAMB is expected to be a primary analysis tool for CMIP6 and future model–data intercomparison experiments. This team developed an initial prototype benchmarking system for ILAMB, which will be improved and extended to include ocean model metrics and diagnostics.

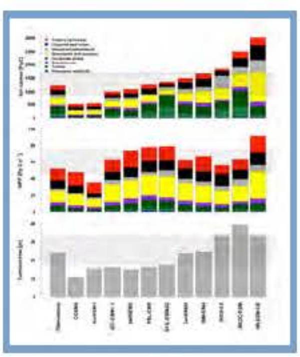

Figure 4: *Global soil carbon (top), net primary production (middle), and soil carbon turnover times (bottom) for ESMs. Gray hashed bars represent the observed 95% confidence limits of the observations. Figure adapted from Todd Brown et al. (2013).*

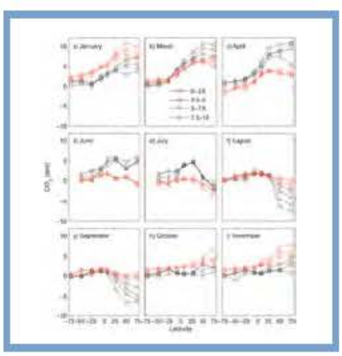

Figure 5: *Free tropospheric CO_2 measured during the HIAPER Pole-to-Pole Observations (HIPPO) campaigns (black) and sampled in the Community Earth System Model (CESM) at corresponding locations (red) for the data averaged into eight latitude bands and four altitude bins. The agreement in vertical CO_2 stratification between CESM and HIPPO observations varied considerably as a function of season, with summer CESM projections generally less vertically stratified than the HIPPO free tropospheric CO_2. Figure adapted from Keppel-Aleks et al. (2013).*

ACCOMPLISHMENTS

Over the past four years, the Carbon–Climate Feedbacks Project that preceded this activity pioneered the development and application of new diagnostic approaches for carbon cycle and ecosystem processes, resulting in 37 peer-reviewed literature publications, plus additional manuscripts in press or in review. Several of these publications focused on benchmarking and analysis of biogeochemistry and land surface processes in the set of phase 5 Coupled Model Intercomparison Project (CMIP5) models available on the Earth System Grid Federation (ESGF). The team also contributed significantly to the development and evaluation of the Community Earth System Model (CESM), focusing on areas of critical uncertainties associated with tropical forest nutrient dynamics, trajectories for forest disturbance, and the state and fate of permafrost carbon.

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BGC Feedbacks Website:
http://www.bgc-feedbacks.org/

International Land Model Benchmarking Website:
http://www.ilamb.org/

Biogeochemical Processes in Earth System Models 10-Year Vision and Long-Term Plan

After the SFA team succeeds in achieving the goals set forth in the SFA Science Plan for the first 3 years of research, we anticipate more phases of scientific investigation aimed at reducing uncertainties in ESMs using best-available observational data, rapidly and comprehensively assessing the performance of ESMs in future phases of the Coupled Model Intercomparison Project (i.e., CMIP6 and subsequent model experiments), and delivering a constantly updated, open-source, model diagnostics package that employs benchmark observational data and informs future model development. While we expect this core activity of the BER's Regional and Global Climate Modeling (RGCM) Program to continue providing valuable research products and international leadership long into the future, here we describe our vision for how this SFA will evolve over the next 10 years.

In the next decade, we anticipate conducting research in three phases. Phase 1 will start in October 2014 and last for three years. Phase 2 will start in October 2017 and extend the SFA for another three years. Phase 3 will start in 2020 and last for four years. Additional phases will be proposed subsequently as this research activity continues to maintain an excellent record of peer-reviewed scientific publications and provide strong international community leadership for model benchmarking and improvement.

The primary questions and hypotheses driving research in Phase 1 are described in the current SFA Science Plan. Hypothesis-driven investigations in Phase 1 will position the SFA to provide the primary ESM evaluation tools for use with carbon, land use, and ocean biogeochemistry model intercomparison projects (MIPs) being designed to complement the Diagnosis, Evaluation, and Characterization of Klima (DECK) experiments for CMIP6 (Meehl et al. 2014). We will achieve this goal through open-source tool development, interaction with the science community through DOE-sponsored workshops and tutorials, and by direct participation by SFA leadership on steering committees for carbon, land use, and ocean biogeochemistry MIPs. Investigators Randerson, Koven, and Hoffman are presently contributing to the design of the coupled climate-carbon cycle MIP (C4MIP) and collaborator Lawrence is organizing the land use MIP (LUMIP) for CMIP6. Moore is currently leading a MIP study examining the impacts of rising atmospheric nitrogen on ocean biogeochemistry and is participating in a second MIP examining the representation of the marine iron cycle and its links with carbon in global-scale ocean models.

During Phase 2 of the SFA, which is projected to last for three years, we will continue to pursue hypothesis-driven research directed at understanding and improving the representation of physical, hydrological, and biogeochemical processes within ESMs. However, because international modeling groups will be contributing CMIP6 simulation results to the Earth System Grid Federation (ESGF) by the middle of 2017, we expect a primary focus of our Phase 2 SFA activities to be on the rigorous evaluation of CMIP6 models. Critical questions we plan to address include: 1) How have biogeochemical, hydrological, and energy predictions in ESMs improved from CMIP5 to CMIP6?, 2) Can we apply new emergent constraints we develop in Phase 1 to the multi-model ensemble from CMIP6?, and 3) Can we facilitate breakthroughs in data-model integration in emerging areas by hosting targeted workshops and tutorials? We also plan to extend the intellectual domain of our project during Phase 2 to include more aspects of ocean biogeochemistry, river and coastal hydrology and biogeochemistry, land use change, food security, aerosols, and atmospheric chemistry. These new foci, examining the land/ocean boundary and aerosol/atmospheric chemistry, are truly Earth system problems that cannot be understood without analyzing the interacting land, atmosphere, and ocean components of coupled ESMs. Both terrestrial and marine systems are sources of aerosols, aerosol precursors, and trace gases that modify atmospheric chemistry and radiative forcing. As representations of these processes are added to ESMs, it is important that the data and metrics are developed in the SFA during Phase 2 to prepare to evaluate models participating in CMIP6 and subsequent model experiments. New driver data sets to support modeling studies and new evaluation data sets from synthesis activities and large-scale analytics will be developed.

While ocean biogeochemistry studies of carbon cycling and oxygen minimum zones (OMZs) are part of the SFA Phase 1 activities, these efforts are significantly smaller in both scope and funding than the terrestrial components of the SFA. In Phase 2, we foresee expansion of ocean biogeochemistry into evaluations of the marine iron, methane, sulfur, and nitrogen cycles as well as their interactions with carbon, ocean deposition, and emission of aerosols and trace gases. Evaluation of river nutrient fluxes and dissolved organic carbon (DOC) in sea ice will be important, but require the synthesis of observations and development of new data sets. Future studies will focus on biogeochemistry-climate interactions, including organic aerosols and the feedbacks with zooplankton. Many ESM groups are currently developing more comprehensive treatment of the zooplankton functional groups that help drive biogeochemistry (i.e., calcifiers, like pteropods and foraminifera) and are also important for fisheries. Similarly, substantial recent research devoted to understanding how atmospheric chemistry impacts the solubility of iron in aerosols has been conducted since the development of the CMIP5 models. Most of the CMIP5 ocean models held atmospheric iron inputs constant. However, most models will likely possess dynamic iron inputs, which respond to both climate change and atmospheric chemistry, in the future. Thus, we expect these processes will be increasingly included in ESMs for CMIP6 and future multi-model experiments, resulting in a rapidly growing need for benchmarks to judge the performance of next-generation atmosphere and ocean models.

Similarly, new demands are being placed on land models to better represent processes within the vegetated canopy. As multi-layer canopy schemes are increasingly adopted to explicitly represent land-atmosphere turbulent interactions and feedbacks, observational constraints on the storage of heat, water, and carbon within the canopy are required. Biogenic volatile organic compounds (BVOCs) emitted by plants oxidize to produce secondary organic aerosols (SOAs), affecting radiative forcing, precipitation, and regional ozone distributions. Isoprene, the single most important BVOC, accounts for almost half of the global total emissions of BVOCs. Woody vegetation also emits monoterpenes and sesquiterpenes, and their reaction products are important sources of SOAs. Some land models, including the Community Land Model (CLM), which incorporates the Model of Emissions of Gases and Aerosols from Nature version 2 (MEGAN-2), have some representation of BVOC emissions. However, significant uncertainties in emission factors for plant functional types (PFTs) and processes governing BVOC production persist in all model implementations. We expect a growing number of models will incorporate multi-layer canopy schemes and BVOC emissions for CMIP6, requiring new efforts to synthesize data from observational campaigns from a variety of forest types and temperature, moisture, and pollution regimes to provide constraints on model predictions. However, while measurements are being made for tropical forests through DOE's GoAmazon2014/15 campaign, more data are needed to effectively assess model performance in extra-tropical ecosystems and under different environmental and air-quality conditions. In Phase 2 of the SFA, we will undertake a synthesis effort directed at developing metrics for evaluating canopy process representations in offline and coupled models participating in CMIP6 and subsequent community model experiments.

The high resolution of the ACME model grid makes it ideal for the study of coastal/estuarine and shelf processes in the oceans, the importance of anthropogenic modifications of the land-to-ocean fluxes of nutrients through riverine runoff, and the influence of ecosystem BVOC emissions on regional climate. These processes are poorly represented in current, coarser-resolution ESMs, and most CMIP5 models did not account for any flux of nutrients to the oceans through river runoff or for bi-directional canopy fluxes. Comparisons of ACME model and the CESM through our benchmarking efforts in Phase 2 of the SFA will help document improvements in the representation of these processes expected to be incorporated into the ACME model, and may point towards tractable parameterizations that could be incorporated into coarser-resolution models like the CESM.

New suites of measurements from NASA satellite remote-sensing platforms, hyperspectral aerial imagery, intensive in situ measurements (e.g., DOE's NGEE Arctic, NGEE Tropics, and SPRUCE projects), and distributed large-scale measurement networks (e.g., AmeriFlux, Fluxnet, NSF's National Ecological Observatory Network (NEON), Smithsonian's Forest Global Earth Observation (ForestGEO), and the Global Ecosystem Monitoring (GEM) network) promise to provide a torrent of observational data with unprecedented resolution and spatial coverage. New remote-sensing technologies can map the chemical and structural traits of plant canopies (Schimel et al. 2013) and tree density (Crowther et al. 2015) and even provide insights into ecosystem processes (Frankenberg et al. 2011). New instrumentation and measurement techniques (e.g., lidar, hyperspectral) from novel platforms (e.g., geosynchronous orbit, drones), along with fortuitous observations (e.g., chlorophyll fluorescence), are expected to greatly advance our ability to observe and monitor land and marine ecosystem structure and function in the coming decade. During Phase 2 of the SFA, we expect to take advantage of data arriving from NGEE Arctic and NGEE Tropics field activities as well as from new satellite platforms, like the Orbiting Carbon Observatory 2 (OCO-2). Having built the tools to manage observational data and perform comprehensive model assessment in Phase 1, we will be well positioned to quickly incorporate new sources of data from advanced sensors and the associated evaluation metrics into our benchmarking package in Phase 2.

Following from the SFA Phase 1 community workshops, we anticipate an array of outreach activities to engage the international modeling and measurement science communities in Phase 2. To accommodate the additional metrics on new, more detailed processes and the burgeoning data volumes from advanced remote-sensing platforms and in situ measurements, we expect increasing demands for project engineering to support and maintain software tools and new data sets developed by the SFA. This need will require continued resources for the computational and technical aspects of the project in Phase 2 and beyond. We anticipate maintaining support for software engineering and model and data developers, as well as making more use of large-scale cyber infrastructure, throughout the lifetime of the SFA.

In coordinated partnership with DOE leadership, we anticipate developing a more formal plan to engage university partners in the final year of Phase 1 and throughout later phases. This plan is critical for building a larger benchmarking community. Specifically, we recommend that DOE BER create opportunities for the university community to extend or apply SFA benchmarking tools in new directions. Examples may include application of our benchmarking system to new model intercomparison activities, the development of new data sets for integration into ILAMB, or new types of model evaluation. Examples of model evaluation might include benchmarking different driver data sets for ESMs, using high-resolution spatial and temporal site data as a check on the gridded data used to evaluate models (benchmarking the benchmarks), and constructing data sets to evaluate high-resolution models (like those being developed for NGEE Arctic and NGEE Tropics). To foster strong integration of university activities with the core SFA team, we anticipate making a request for science staff to provide community support (as a liaison) and more SFA funds to cover short-term and sustained university partnerships.

Looking 6 years out is challenging in the rapidly advancing science of Earth system modeling. DOE's NGEE projects will be generating a peak amount of data, new satellite missions will be streaming wall-to-wall hyperspectral data to Earth, unmanned drones will be imaging tree canopies and monitoring leaf- to ecosystem-level gas exchange, and the modeling community will be designing experiments for CMIP7. Likewise, we anticipate a significant step change in effort and scope during Phase 3 of the SFA. Expanding upon our participation in MIPs complementing the DECK experiments for CMIP6 and our leadership in rapid and comprehensive model evaluation, we anticipate leading for DOE the design of at least one terrestrial and one ocean biogeochemistry MIP for CMIP7. We further expect to develop new methods for integrating models and data, including implementing data assimilation methods to produce new state-of-the-science carbon inventories, land and ocean biomass distribution data incorporating land use and circulation changes, and initialization data sets for commonly used terrestrial and marine models.

We plan to extend our international leadership in ESM research by building a National ESM Analysis Center (NESMAC). NESMAC will maintain all of the functionality developed from the SFA during Phases 1 and 2, but will have a much broader mission of increasing interaction between modeling and observational communities for informing the sustainable management of Earth's biogeochemical, hydrological, and energy cycles. NESMAC will develop new tools for lowering barriers to collaboration and integration between observational and modeling communities, will solicit small synthesis proposals from the community for working groups (analogous to those of the National Center for Ecological Analysis and Synthesis (NCEAS) and the National Institute for Mathematical and Biological Synthesis (NIMBioS)), and will train the next generation of PhD students and postdoctoral researchers in Earth system science. NESMAC will unite experimentalists and field researchers with modelers and systems engineers to co-design CMIP7 experiments, advanced remote sensing instruments, and manipulative field experiments targeted at answering critically important science and sustainability questions.

We anticipate working jointly with DOE, NSF, NASA, NOAA, non-governmental organizations (NGOs), environmentally conscious foundations, and university partners to develop this center at a yet-to-be-decided-upon location favorable for promoting the interactions among these science communities. Through multi-agency support and featuring an international footprint, we anticipate funding levels to approach ~$10M per year. Yet the center will maintain the scientific rigor and steadfast advocacy for open science cultivated in the earliest Phase of the SFA. We expect the NESMAC to operate for at least a decade, with a rigorous evaluation and renewal phase at the end of the first 4 years. NESMAC will be a key asset in DOE's modeling research portfolio, with strong ties to DOE's advanced computing and ecosystem science programs.

Table 1: The 10-year vision is summarized, and intermediate goals for achieving the vision are identified

ILAMB and Benchmark Tools	ILAMB prototype and second-generation system, integrate C cycle metrics into ESGF	Ocean benchmark integration, full integration into ESGF	Server-side benchmarking and offline transport / runoff model integration
Community Engagement and Leadership	AGU Town Hall, ILAMB community workshops, ILAMB tutorial	AGU and AGU Ocean Town Halls, land / ocean community workshops, benchmarking tutorials	Build multi-agency ESM Center, land and ocean community workshops, synthesis working groups
Metrics Development	Develop and test emergent constraint approach, land / ocean C cycles, OMZs, atm C distribution	DOC in sea ice, ocean organics and aerosols, land VOCs and SOAs, soil types, plant traits, atmospheric chemistry	Coastal / estuarine processes, riverine nutrients, bi-directional canopy fluxes
Forcing Data Development	Evaluate land model sensitivity to forcing, test alternative forcing data	Contribute to development of new forcing data for land and ocean models	Develop state of the carbon cycle data / initial conditions through assimilation
Evaluation Data Development	Global carbon, water, energy data, high-lat soil C, AmeriFlux, FACE / N addition / warming experiments	NGEE Arctic / Tropics and SPRUCE data, Fluxnet, lidar / hyperspectral, OCO-2, add uncertainty data	Synthesis / analytics for combining data, new in situ data from drifters / drones
MIP Experiment Development and Analysis	C4MIP and LUMIP for CMIP6, TRENDY for Global Carbon Project, PLUME-MIP	Evaluate CMIP6, lead land / ocean / atm biogeochemistry MIPs for CMIP7, other MIPs	Perform CMIP7 experiments, evaluate CMIP7

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Enabling Capabilities and Connections Across SFAs and Projects

#	SFA Theme/Project	D&A	Extreme Events & Tipping Points	Climate Feedbacks and Process interactions	Uncertainty Characterization	Test beds
1a	CVC and Cloud Processes (LLNL)	Formal identification of anthropogenic fingerprints in several atmospheric and oceanic variables, including temperature, heat content, water cycle, and clouds.	Role of variability and changing mean state on future drought.	Cloud climate feedbacks; feedback methodology.	Use of ensembles of observations and models to gauge consistency of findings.	CAPT for evaluating new parameterizations of clouds and other atmospheric processes as well as coupled atmosphere-land and atmosphere-ocean processes.
1b	CVC, feedbacks, predictability and prediction (UCAR CA)	Single forcing experiments.	High-resolution work; how extremes and daily records change in a changing climate.	Cloud processes and paramater uncertainty in PPEs; CFMIP analyses; decadal climate variability processes and mechanisms.	Large ensembles; probabilistic climate change information from decadal hindcasts.	CAPT for coupled atmosphere-land and Atmosphere-ocean processes.
2a	High Latitude Feedbacks (HiLAT)	We are planning to perform 1) a detection and attribution study of Greenland Ice Sheet melt, and 2) a sutdy of impacts of high-latitude cryosphere change on mid-latitude climate.	Our project will study the behavior of Arctic sea ice, and the AMOC. Both systems are (were?) suspected to contain thresholds (although those are not the focus of the project).	HiLAT will address 1) local feedbacks involving cryospheric changes and high-latitude climate features, and 2) the global climate system (through polar/extra-polar exchanges) of high-latitude processes. Some of the feedbacks are: cryosphere-marine BGC-aerosols-clouds; Antarctic Ice Sheet-Antarctic sea ice -albedo; Arctic cryosphere-AMOC; Antarctic cryosphere-Antarctic Bottom Water formation; cryosphere-atmospheric circulation-polar/extrapolar exchanges; and water vapor-lapse rate feedback.	Gaussian Process Emulators and parameter estimation, specifically for sea ice; probababilistic scenarios for ice-sheet discharge; ensemble simulations to evaluate contributions of various forcing agents and feedback mechanisms.	Testbeds with a focus on the Arctic and Antarctic.
2b	Regional Arctic System Model (RASM)			Decadal Climate feedbacks in the Arctic.		Testbed for Artcic processes.
3	Water Cycle (WACCEM)		High-Resolution and Mesoscale Processes, Atmospheric Rivers.			Using MPAS variable resolution simulations as testbeds for scale-aware parameterizations.
4	Extremes (CASCADE)	D&A of extremes.	Statistics, D&A of extremes, processes related to extremes.		UQ of D&A statements*	ILIAD
5	BGC Feedbacks SFA (BGC Feedbacks)	Ongoing: Analysis of LAI and related terrestrial prognostic fields using D&A methods (Mao et al.).	Future: How extreme events affect BGC processes on land and in the ocean.	Ongoing: Biogeochemistry-climate feedbacks in the terrestrial and marine systems.	Ongoing: Land model sensitivity to meteorological forcing data sets, spatial uncertainty estimates of below-ground properties. Future: Land and ocean sensitivity to initial conditions, boundary conditions, and parameters.	Future: Testbed for site-level comparisons, experimental manipulations, functional response metrics, and large-scale patterns.

#	SFA Theme/Project	Metrics to evaluate models	Diagnostic Tools	MIPs	Hierarchy of Models	Regional Modeling
1a	CVC and Cloud Processes (LLNL)	Metrics Package for climatologies; noise metrics; error quantification.	Satellite simulators for evaluating model cloud properties and cloud radiative feedbacks, APRP, "kernel" approach to cloud-climate feedbacks evaluation, MSU "temperature".	MIP leadership (expt. design, infrastructure requirements, output request, boundary conditions), contributing especially CMIP, CFMIP, OMIP, DAMIP, RFMIP, obs4MIPs, PMIP, and geoMIP, with analysis focussed on D&A, clouds, feedbacks, and other selected phenomena.	Application of EBMs, AGCMs, AOGCMs, and ESMs to study feedbacks and climate processes.	D&A at regional scales; multi-model intercomparison project (CAUSES) to understand the causes of warm biases in surface temperature over summertime middle-latitude land masses.
1b	CVC, feedbacks, predictability and prediction (UCAR CA)		Climate Variability Diagnosis Package; NCL.	Will run simulations for ScenarioMIP, CFMIP, DAMIP, DCPP, LS3MIP, LUMIP, PMIP; CMIP leadership.	Aqua planet, CAM, Atmospheric Models Coupled mixed layer.	
2a	High Latitude Feedbacks (HiLAT)	Enhancements to existing aerosol and cloud metrics package for high latitudes.	Water (vapor, and condensed phases) tagging to provide insight into the water cycle at high latitudes. We hope to enhance interactions with the COSP activity.	ISMIP; SIPN; OCMIP; we have a latent connection with AMOCMIP (Schmittner et al.), but no simulations to contribute; we will participate and contribute to AEROCOM if our initial 3-yr activities produce relevant new tests.	Individual component land-ice sea-ice, and atmosphere models; Arctic Terrestrial Simulator; 1 degree and 0.3 degree versions of ACMEv0; regionally refined ACMEv+ configurations.	Arctic and Antarctic
2b	Regional Arctic System Model (RASM)					Arctic
3	Water Cycle (WACCEM)	Metrics based on relationships between large-scale circulation features (e.g., atmospheric rivers and jet stream) and relationships between large-scale circulation features and regional phenomena.	FAWA, last saturation tracer model, cloud tracking, land-atmosphere interactions, diabatic heating and circulation, large-scale environment for tropical cyclone.	HighResMIP - analysis focus on monsoon, atmospheric rivers, interactions between convection and large-scale circulation; ITCZ/MonsoonMIP - analysis focus on monsoon in idealized simulations; analysis of atmospheric rivers and monsoon from CMIP5.	MPAS: Aquaplanet (including various configurations with idealized continents/mountains), AMIP, Atmospheric Models coupled with mixed-layer ocean ; ACME: coupled simulations.	MPAS with refined regions over the US, Amazon, and Asia.
4	Extremes (CASCADE)		TECA; Atmospheric Rivers, TCs, Midlatitude Cyclones; fastKDE for multivariate PDF analysis; LLEX R package for extreme value analysis; Event detection with deep neural nets.*	C20C, Analysis of extremes in CMIP models.	Aquaplanet, CAM, CRMs*, adaptive mesh refinement models.*	Regional modeling for D&A studies.
5	BGC Feedbacks SFA (BGC Feedbacks)	Ongoing: ILAMB system metrics for land and initial metrics for ocean biogeochemistry. Future: New metrics for experimental manipulations and functional responses.	Ongoing: ILAMB prototype system nearly final, second-generation ILAMB system under development. Future: Automated ocean evaluation system, high-level model benchmarking architecture and testbed interconnectivity.	Ongoing: Participation in C4MIP, LUMIP (with NCAR-CA), OCMIP experimental design and planned multi-model benchmarking and analysis. Future: Design of future experiments for CMIP7, international workshops for measurements and modeling communities to design integrated experiments.	Ongoing: Evaluating land-only, land + atmosphere, and fully coupled model configurations. Future: Support for offline transport and surface runoff models, support for multiple land model configurations in ensemble simulations, new ocean biogeochemistry configurations.	Ongoing: tropics. high-latitude, and midlatitude analysis. Future: Regional model evaluation at basin scales.

#	SFA Theme/Project	Atmospheric /ASR-ARM	Terrestrial/TES	ACME/ESM	IARP	Data
1	**CVC and Cloud Processes (LLNL)**	CAPT analyzes climate model simulations of cloud and associated processes with ARM data - note joining of LLNL ASR SFA with LLNL RGCM SFA; Incorporation of ARM data into obs4MIPs; ARM metrics for use with CMIP models.		Analysis of ACME model through application of PCMDI Metrics Package and CAPT simulations and analysis.	Contributions to Integrated Assessment Model Intercomparison (PIAMDDI).	Link CMIP community with ESGF developers to optimize usage of CMIP archive; integrate metrics framework with ESGF data archive.
1	**CVC, Feedbacks, predictability and prediction (UCAR CA)**	CAPT, Cloud feedbacks, and applying model hierarchy.	iLAMB and analysis work led by Dave Lawrence.	analysis of ACME simulations to address science questions in the CA.	Connections through work done by Claudia and Ben, Scenario MIP simulations.	running CMIP6 simulations, metrics framework and ILAMB.
2	**High Latitude Feedbacks (HiLAT)**	Atmospheric component led by Phil Rasch and potential testbed for ARM Arctic measurements.	Connections with NGEE-Arctic through Rowland and Wilson at LANL.	Arctic/Antarctic regionally refined versions of ACME.		
2	**Regional Arctic System Model (RASM)**	Atmospheric component led by John Cassano?				
3	**Water Cycle (WACCEM)**	SGP site and mesoscale processes; atmospheric rivers; land-atmosphere interactions.	Land-atmosphere interactions in Amazon.	Analysis of ACME and similar analysis using MPAS.	Regional Modeling capabilities over the US, connection of tropical cyclone research with coastal infrastructures.	HighResMIP.
4	**Extremes (CASCADE)**	ILIAD for looking at land-atm feedbacks (w/ I. Williams).		TECA in ACME.	Extremes and water cycle.	Use of ESGF for C20C+.
5	**BGC Feedbacks SFA (BGC Feedbacks)**	Ongoing: Atmospheric transport modeling of carbon dioxide. Future: Atmospheric tracer and aerosol transport and evolution.	Ongoing: ILAMB, NGEE Tropics (Charlie Koven); NGEE Arctic (Bill Riley); ORNL TES SFA (Xiaojuan Yang); Arctic soil carbon (Umakant Mishra); DOE-funded university projects: CSU, PSU, Umn; LBNL Soil warming experiment; Possibly others.	Ongoing: Analysis of ACME model and ILAMB embedded in ACME Testbed.	Ongoing: None at present. Future: Model scoring for better interpretation of climate change projection results for impacts analysis.	Ongoing: ILAMB (multi-model output from ESGF, forcing and evaluation data from AmeriFlux, CDIAC, ARM, NGEE Arctic and Tropics). Future: Synthesis and meta-analysis of observations, model-data integration, large-scale data analytics, development of emissions and forcing data sets for global experiments, development of integrated or derived remote sensing data sets.