ACME
Accelerated Climate Modeling for Energy

The Accelerated Climate Modeling for Energy (ACME) project is sponsored by the U.S. Department of Energy's (DOE's) Office of Biological and Environmental Research (BER) to develop and apply a computationally advanced climate and Earth system model to investigate the challenges posed by the interactions of climate change and societal energy requirements.

The ACME model simulates the fully coupled climate system at high-resolution (15-25km) and will include coupling with energy systems, with focus on a near-term hindcast (1970-2015) for model validation and a near-term projection (2015-2050) most relevant to societal planning. The model further employs regional-refinement using advanced adaptive mesh methodologies in order to provide ultra-high-resolution to resolve critical physics and meteorological phenomena. The ACME model branched from the Community Earth System Model (CESM), and increasingly, its code will be designed to optimize performance on current and future DOE Leadership Class computers.

ACME's initial scientific goals address three areas of importance to both climate research and society:

1. **Water cycle:** How do the hydrological cycle and water resources interact with the climate system on local to global scales?
2. **Biogeochemistry:** How do biogeochemical cycles interact with global climate change?
3. **Cryosphere-ocean system:** How do rapid changes in cryosphere-ocean systems interact with the climate system?

The ACME project was constructed from existing DOE climate modeling resources and is distributed across eight DOE national laboratories and six partner institutions.

Climate Science Objectives

WATER CYCLE

Understanding and developing the capability to project the evolution of water in the Earth's system is of fundamental importance both to climate-science and to societal and many energy-related processes, including coal-, nuclear-, biofuel-, and hydro-power potentials.

Using river flow as a key indicator of hydrological changes from natural and human systems, ACME is testing the hypothesis that changes in river flow have been dominated by land management, water management, and climate change associated with aerosol forcing but will be increasingly dominated by greenhouse gas changes.

The initial phase of the project focuses on simulation of precipitation and surface water in orographically complex regions, including the western United States and the headwaters of the Amazon. Improved resolution and parameterizations of clouds, aerosols, and their interactions, should produce a more realistic portrayal of the precipitation location, frequency and intensity, as well as aerosol deposits on snow and surface ice—all factors that influence runoff, snowpack, and snowmelt. ACME explores the role of these various physical processes in influencing river flow and fresh water supply, with a goal of simulating an accurate portrayal of present-day river flow for major river basins on the planet.

The longer-term water cycle goal is to understand how the hydrological cycle in the fully coupled climate system will evolve with climate change and the expected effect on local, regional, and national supplies of fresh water.

ACME will further examine whether during the next 40 years, the additional forcing from increasing greenhouse gas concentrations will come to dominate river flow changes.

	Questions	Near-term (3-yr) Experiments	Long-term (10-yr) Experiments
WATER CYCLE	**What are the processes and factors governing precipitation and the water cycle today, and how will precipitation evolve over the next 40 years?**	How will more realistic portrayals of features (resolution, clouds, aerosols, snowpack, river routing, land use) affect river flow and associated freshwater supplies at the watershed scale?	How will the integrated water cycle evolve in a warmer climate with changes to land and water use, and changing forcing agents (aerosols, greenhouse gases)?
BIOGEOCHEMISTRY	**What are the contributions and feedbacks from natural and managed systems to current and future greenhouse gas fluxes?**	How do carbon, nitrogen, and phosphorus regulate climate system feedbacks, and how sensitive are these feedbacks to model structural uncertainty?	How will coupled terrestrial and coastal ecosystems drive natural sources and sinks of carbon dioxide and methane in a warmer environment?
CRYOSPHERE-OCEAN SYSTEM	**What will be the long-term, committed Antarctic Ice Sheet contribution to sea-level rise from climate change during 1970–2050?**	Could a dynamical instability in the Antarctic Ice Sheet be triggered within the next 40 years?	How will regional variations in sea-level rise interact with more extreme storms to enhance the coastal impacts of sea-level rise?

Table 1. Summary of primary science driver questions

BIOGEOCHEMISTRY

The degree of carbon exchange between terrestrial and atmospheric components is key for investigating human influences on atmospheric carbon dioxide (CO_2) and elemental carbon particle concentrations, yet this exchange is in turn affected by climate change and nutrient availability.

The early phase of ACME is examining how more complete treatments of nutrient cycles affect carbon–climate system feedbacks, with a focus on tropical systems. ACME is also investigating the influence of two alternative model structures for below-ground reaction networks on global-scale biogeochemistry–climate feedbacks. ACME is adding phosphorus (P) to its below-ground carbon-nitrogen nutrient system, since P availability may limit tropical ecosystem production and may play an important role in regulating global-scale feedbacks among CO_2 concentration, temperature, and the hydrologic cycle. The systems will be further tested and utilized to study hydrology and carbon fluxes in the Arctic tundra and other high-latitude systems.

Tropical land-atmosphere-climate dynamics will be investigated by ACME and companion BER research.

Experiments will investigate the nutrient and climate interactions for the preindustrial through the 21st century.

A longer-term goal is to study interactions between land and coastal ecosystems, particularly for high-latitude systems. The combination of coastal-zone biogeochemical cycling and its interaction with the silt, nutrients, and other substances transported by rivers and runoff is one of the major unsolved grand challenges in carbon-cycle research.

CRYOSPHERE-OCEAN SYSTEM

As ACME builds and couples new dynamic ice sheet and ocean components, it will simulate the potential for the Antarctic Ice Sheet melt, destabilization and sea-level rise. These simulations will utilize the variable-mesh capabilities to enhance resolution in the ocean near the ice sheet and in active regions of the ice sheets. The Model Prediction Across Scales, or MPAS-Ocean, will resolve eddies to better represent the circumpolar deep water and dynamics associated with bringing this water onto the continental shelf under the ice sheet, with ocean model resolution attaining 5km or less near the ice sheets, and the ice sheet resolution up to 500m near the margins. Sea ice modeling is also crucial to capture the processes of buttressing at the ice shelf-sea ice boundary, including the development of ice calving dynamics and ice-berg models. In the fully coupled system, climatic changes in atmospheric general circulation will also influence the behavior of the Southern Ocean and sea ice. The ACME MPAS-Ocean and ice developments are implemented and analyzed in the Arctic by a companion DOE-sponsored project.

In the long-term, ACME will include components required to simulate impacts of sea-level change and storm surge on coastal regions, including wave models and focusing resolution in coastal and storm-track regions.

Computational Science Objectives

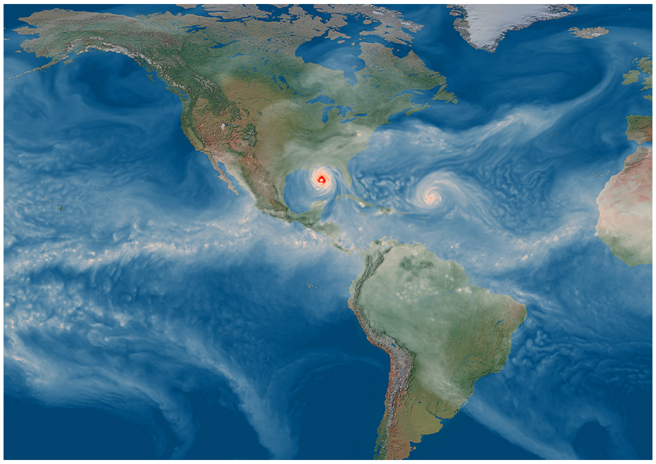
A major motivation for the ACME project is the paradigm shift in computing architectures and their related programming models as capability moves into the exascale era. DOE, through its science programs and early adoption of new computing architectures, traditionally leads many scientific communities, including climate and Earth system simulation, through these disruptive changes in computing.

PERFORMANCE

ACME is optimizing and adapting climate code performance for current and next-generation DOE Computer Facilities, particularly those at the Argonne Leadership Computing Facility, the Oak Ridge Leadership Computing Facility, and the Lawrence Berkeley National Laboratory National Energy Research Scientific Computing Center. Future computer architectures will be constrained primarily by limits on power consumption, resulting in more complex-processor machine architectures that have more computational cores per processor, and less memory per core. The climate codes will therefore be required to support stricter memory management and more complex thread management. In addition, the power and latency cost of communication across the memory hierarchy will significantly affect performance.

The ACME performance "gold-standard" is to maintain a coupled–model speed of five simulated years per wall-clock day, even while moving to higher resolution. ACME focuses on exposing increased concurrency throughout the model and on increasing the on-core

ACME will develop the physics of ice-ocean interactions at the ice sheet margins. Image courtesy of Amanda Graham from flickr.com.



An example hurricane simulated by the ACME model at high resolution. Precipitable water (gray scale) shows the detailed dynamical structure in the flow. Strong preciptiation is overlaid in red. High resolution is necessary to simulate extreme events, such as Category 4 and 5 tropical cyclones.

performance of key computational kernels. Initially the project is implementing conventional approaches, such as threading and message-passing while increasingly employing the use of on-processor accelerators added in the latest machine designs. Redesigning code for better concurrency through the use of modularized kernels for accelerators will be beneficial for most envisioned exascale architectures. In the longer-term, ACME will explore dynamic autotuning and load balancing—even work stealing—to minimize latency and make the application resilient to system disruptions from the higher failure rates and aggressive power management strategies anticipated on exascale architectures.

SOFTWARE ENGINEERING

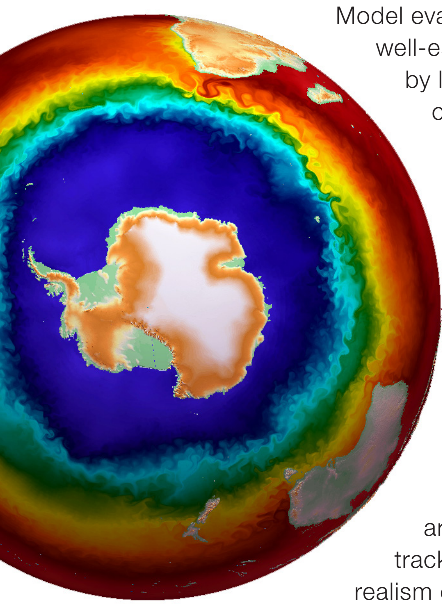
Immediate priorities for ACME software engineering include maintaining build, test, and performance tools on at least five of the relevant computer platforms, and providing rapid development and debugging capabilities to the team. With the ACME focus on delivering a coupled model, the code repository needs to expedite the merging and testing of the fully coupled system. The repository must support a distributed development environment where separate features are being co-developed at different sites, and must also support ongoing development in separate branches with sophisticated tools for merging.

In the longer-term, ACME will expand use of regression testing, tools for code coverage, correctness analysis, debugging at scale, and traceability of code back to scientific requirements. Productivity will be enhanced by greater use of libraries, frameworks, and tools that can be shared across the extreme-scale scientific computing community.

Simulating land biogeochemistry-water-climate interactions will improve understanding of vegetation evolution and biofuel potentials.

WORKFLOW AND VALIDATION

The ACME workflow team is developing tools that will simplify and automate the processing, analysis and validation of the model output. Its workhorse is based on the Ultrascale Visualization Climate Data Analysis Tools software and ACME component, and coupled simulation output will be processed on a single workflow platform. Importantly, the software can accommodate the very large data sets from the ACME high-resolution simulations and it will enable "server-side" analysis of output rather than requiring porting of output to local machines. The analysis provenance will be captured, to enable replication of the process. Model output will be hosted and shared through the Earth System Grid Federation, using a CMIP5-friendly format.



Model evaluation is initially based on well-established metrics developed by leading global modeling centers. Availability of new observations, a focus on the ACME driving questions, and emphasis on high-resolution require development of new diagnostics and metrics; this effort will be a major thrust of the ACME project. Since the emphasis of ACME is on the coupled system, component metrics will generally be evaluated in the coupled system. Metrics are being established that will track model improvement and realism of the coupled system.

Project Structure

At inception, the ACME project spans eight DOE National Laboratories (Argonne, Brookhaven, Los Alamos, Lawrence Berkeley, Lawrence Livermore, Oak Ridge, Pacific Northwest, and Sandia), four academic institutions (University of Maryland, University of California – Irvine, Scripps Institute of Oceanography, New York Polytechnical Institute), the National Center for Atmospheric Research, and the private company Kitware. ACME is led by a council of 12 senior scientists who span the project disciplines and institutions and have final authority on all major project decisions, with a higher level of leadership from the Executive Council.

The ACME project is sponsored by the Earth System Modeling program in the Office of BER. Important collaborations with other BER programs include model metrics development with Regional and Global Climate Modeling, integration with energy and societal elements with Integrated Assessment Research, land and atmosphere parameterization development through Environmental Systems Sciences and Atmospheric System Research, and data system approaches from Data Informatics. Collaborations with the Office of Advanced Scientific Computing Research are essential for the computational objectives in ACME.

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A project of the **Climate and Earth System Modeling** program

U.S. DEPARTMENT OF ENERGY | Office of Science

BIOLOGICAL AND ENVIRONMENTAL RESEARCH
Climate and Environmental Sciences Division