DOE Climate and Earth System Modeling Program

CESM Activities

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Climate and Earth System Modeling
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CESM Advisory Board meeting
Energy is the defining challenge

• The major driver for
  – *Climate change*
  – National security
  – Economic competitiveness
  – Quality of life

• Incremental changes to existing technologies cannot meet this challenge
  – Transformational advances in energy technologies are needed
  – Transformational adaptation strategies will need to be implemented
  – Transformational changes to tools enabling virtualization of strategies

• CESM is DOE’s climate projection tool of choice

The mission of the Energy Department is to ensure America’s security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.
CESM for Energy requirements

- High-resolution climate projections with skill quantification
- Provide Water and Energy projections for stakeholders
- Terrestrial and Agriculture impacts and feedbacks
- Sea-level change and coastal infrastructure impacts
- Arctic changes
CESM benefits from the partnership between Climate and Computation Offices, allowing co-funding and close coordination between computer and climate research.
DOE and CESM priorities

1. Advance the Energy mission by providing high-resolution climate projections, including coupling to human components (e.g. the integrated Earth System Model project that couples GCAM to CESM), ocean and cryospheric systems.

2. Advance atmospheric research

3. Advance terrestrial research

4. Utilize computational expertise and Leadership Class Computers in service of 1-3
1. CLM 9M (includes “human” processes)
2. CAM, aerosols, clouds, chem 7M
3. POP, MPAS, ocean biogeochemistry 6M
4. CISM, CICE 2.4M
5. Coupled system 3M
6. “Testbeds” 4M
7. Visualization 4M
IMPACTS: INVESTIGATION OF THE MAGNITUDES AND PROBABILITIES OF ABRUPT CLIMATE TRANSITIONS
Collins PI, 2008-13

- Methane: from clathrate sediments, in water column, atmosphere
- Boreal Arctic feedbacks: Methane biogeochemistry, lake upgrade in CLM
  Shrub height feedbacks (Bonfils et al., ERL, 2012; IOP select paper)
- Megadroughts, positive feedbacks from Vegetation, soil (CLM4VIC)
  Dust
- Ice-sheet – ocean interface, important for simulation of WAIS stability
- POP adjoint for AMOC stability

LANL
PNNL
LLNL
LBNL
ANL

Bonfils et al., 2012
Reagen et al, submitted
“Polar”: Improving the characterization of Clouds, Aerosols and the Cryosphere in Climate Models
2009-2013 Jones, Rasch PI’s

Cryosphere, ocean:
- Sea-ice strength, melt rates: chlorophyll, salinity effects
- Ice sheet mass-balance
- Arctic ocean circulation
- Ocean biogeochemistry

Atmosphere:
- Aerosol transport and deposition
- Arctic clouds, COSP simulator

Coupled Systems

(a) CAM51_SOM (All)
(b) CAM51_SOM (CO2)
(c) CAM51_SOM (Aerosol)
(d) CAM51_SOM (OHT)
iESM: Improving the Representation of Human-Earth System Interactions, 2009-13

- Create a first-generation iESM with both the human components of an integrated assessment model (GCAM) and the CESM

- PNNL (Edmonds), LBNL (Collins), ORNL (Thornton) and the U of Maryland

- First version of code coupling land systems of GCAM and CESM is largely complete and being prepared for release to the CESM community.

- AGU Session at Fall 2012 meeting

Initial experiments focusing on land use illustrate the importance of including albedo effects of land use change in future calculations of radiative forcing (submitted to Science)
**Ultra High Resolution Global Climate Simulation to Explore and Quantify Predictive Skill for Climate Means, Variability and Extremes**

Hack, PI, 2010-14

- Simulate climate, non-linear interactions at very high resolution (T85, T341)
- Extremes

- Balancing, tuning is challenging!
- Land-model spin-up slow
- Migrating to CAM-SE, will benchmark variable mesh simulations

- POP, CICE at 0.1 degrees;
- Initialization challenges
- Influence of CICE on AMOC

- High-res Aerosol effects on climate: black carbon stabilizes marine stratus

**ORNL, LANL, LLNL, LBNL, Scripps, SNL**
Cross-cutting Themes and Labs to advance CESM to address high priority DOE climate research

**Testbeds for CESM:**
Uncertainty Quantification and data for model calibration

**3 Components:**
- Atmosphere
- Land
- Ocean and Sea-Ice

**3 Research Directions:**
- Hydrologic simulation improvement
- Variable-resolution numerical methods
- Carbon cycle uncertainty reduction

**9 Labs:**
- ANL
- BNL
- LANL
- LBNL
- LLNL
- ORNL
- PNNL
- SNL
- NCAR
1. Multiscale Methods for Accurate, Efficient, and Scale-Aware Models of the Earth System
Bill Collins, PI
LBNL, LANL, PNNL, ORNL, SNL, UCAR, UW-M, CSU, UCLA

Will introduce accurate and computationally-efficient treatments of interactive clouds, convection, and eddies into the next generation of CESM at resolutions approaching the characteristic scales of these structures and deliver these process treatments and constituents that are scientifically useful over resolutions ranging from 2 to 1/16 degrees.
2. Predicting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES)
Bill Lipscomb, PI
LBNL, LANL, ORNL, SNL, UCAR, MIT, FSU, U-SC, UT-Austin

Develop two ice sheet dynamical cores:
1) finite-volume, structured, Chombo adaptive mesh
2) finite-element, unstructured MPAS mesh

3. Applying Computationally Efficient Schemes for BioGeochemical Cycles (ACES4BGC)
Forrest Hoffman, PI
ORNL, SNL, LLNL, PNNL, LANL, ANL, UCAR

1) new tracer advection scheme, supporting thousands of species in atmosphere and ocean models
2) Improving organic emissions, chemistry
Climate model analysis and visualization 2010-2013, 3 projects

1. Ultra-scale Climate Data Analysis Tools (UV-CDAT)  
   Williams, PI

2. Visual Data Exploration and Analysis of Ultra-large Climate Data  
   Bethel, PI

3. “parVis”  
   Jacob, PI

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Utilize computational expertise and Leadership Class Computers

1. AGU Town Hall (Dec 2012)
2. “Next Generation Innovations in Climate Modeling” DOE workshop (Dec 2012)
3. “Extreme-Scale Software” Summit – tomorrow...

Extreme-Scale Application Software Productivity Summit

28 February 2013 DOE, Germantown, MD 20874

Summit Objective:
The main objective of this summit is to explore potential research challenges and opportunities in applications software productivity/software engineering at extreme-scale, in light of extraordinary advances in multicore computing hardware and new programming paradigms. The summit will also explore strategies that can enable computer scientists and domain scientists to co-develop applications software for complex multiscale and multiphysics problems that take full advantage of recent advances in multicore computing technologies and on-going best practices in HPC applications software development.
DOE Climate model development workshop (retreat): “Next Generation Innovations in Climate Modeling”
Berkeley (LBNL), December 8-9, 2012
DOE Climate PI’s (12) and Computational (6) experts

Objectives:

A) What are DOE scientific objectives for climate modeling and leadership class computing?

B) What are the challenges posed by newest computer architectures, and how might DOE address these?

C) How might DOE climate model development program best restructure to facilitate these?
B) What are the challenges posed by newest computer architectures, and how might DOE address these?

- These challenges are considerable!

ExaScale systems aren’t just bigger versions of the current PetaScale systems. The degree of concurrency as well as increasingly complex processors means that existing algorithmic and software approaches no longer work (Greenough, et al., 2011, EESI).

- These are faced by climate centers and groups worldwide (e.g. MPI, ECMWF has exascale projects)

- These are faced across DOE Science Offices

Implicit Imperative to be INCITE/ALCC competitive!

- Partnerships between Climate and Computing within DOE as in the SciDAC program may be further exploited to advance CESM.

- Long-range and broad vision is to develop flexible code designs to be most adaptive to future architectures, both for CESM and for the broader climate community
4.1 A grand challenge: Towards 1 km global resolution

A “grand challenge” for the longer term is to develop global climate models which resolve convective scale motions (nominally around 1km horizontal resolution). Although ostensibly this challenge is only about resolution, ENES believes that addressing this challenge will also support nearly all of the other scientific goals outlined earlier.

Prepare for future computer architectures

We need developments that enable systems to deliver for the fully coupled ESMs, including I/O, a much higher efficiency (sustained performance over peak performance) than today given the raw peak performance increase to be expected from future systems at the same price range.

There is a need to revisit the dynamical part of atmosphere and ocean models in terms of the underlying equations and their discretisation and numerical solution – possibly on new types of grids – to make them better suited for a large number of
“Next-Gen” Workshop: Adapting code to evolving Leadership Class Facility LCF machines

- Expose parallelism, within climate processes (very challenging!)
- Reduce data motion in code (very challenging)
- Sustain portability – enable flexible adaptation for future architectures
- Code abstraction to buffer climate developer from hardware
  Holy Grail of HP climate modeling: NRC report
  “Common software infrastructure”
- Expand Library utilization.
- Create mini-apps for co-design
- Resilience and fault tolerance
- Parallelism challenges with multi-scale, multi-physics
“Next-Gen” Workshop: Code testing and workflow

1. More unit tests (code bits for testing)

2. New code impact on performance

3. New code impact on climate, to find “bugs”
   Automated compile and run-time diagnostics for rapid debugging

4. **New code impact on climate-system, analysis
   Postprocessing climate performance of component and whole-system
   Automated and systematized postprocessing of climate performance for components and for whole-system

5. **Methods to assess uncertainty of climate projections (using hind-cast model performance)

**Multi-lab project “Climate Science for a Sustainable Energy Future” is addressing workflow automation and UQ
“Next-Gen” Workshop: Build system

Automated, provenance, machine-aware build system for various configurations

Automation for input file gridding

Coupling issues

Management of interfacing, fluxes across multi-scale, multi-physics boundaries (e.g. ocean-atmosphere)

Flexible interfacing to enable “interoperability”

Implicit treatments for time integration, flux transfers

Performance impacts of new grids
“Next-Gen” Workshop: Uniformity of development practice

Developers are diverse in skill and dispersed geographically

Education in code practice and testing

Beyond Fortran

Distributed code repository?

Better documentation approaches

Long-term fostering of cadre of individuals with both computational and climate skills
“Next-Gen” Conclusions

DOE needs increased resolution, ensemble runs with increased resolution requires effective use of the “LCF’s”, use of LCF’s requires substantial code upgrades. The exact form these will take are in planning stages: Discussions with ASCR, discussions with NCAR-CSEG.

Climate projection with uncertainty characterization requires improved coupled-system perspectives.

Therefore DOE-Lab model development program will be shifting from a multi-project structure to a few-component structure, with embedded computational expertise and guided by coupled-system leadership.

These new directions will benefit CESM overall, with DOE providing more focused development and greatly enhanced capabilities for high-resolution simulation on the fastest machines.
CESD Strategic Plan is just released:

Goals:

1. **Synthesize new process knowledge and innovative computational methods advancing next generation, integrated models of the human-earth system.**

2. **Develop, test and simulate process-level understanding of atmospheric systems and of terrestrial ecosystems extending from bedrock to the top of the vegetative canopy.**

3. **Advance fundamental understanding of coupled biogeochemical processes in complex subsurface environments to enable systems-level prediction and control.**

4. **Enhance the unique capabilities and impacts of the ARM and EMSL scientific user facilities and other BER community resources to advance the frontiers of climate and environmental science.**

5. **Identify and address science gaps that limit translation of CESD fundamental science into solutions for DOE’s most pressing energy and environmental challenges.**
“Next-Generation” Workshop

Science Framework: 80 year ultra high-resolution simulation
1970-2010: hindcast automated testbed against measurements
2010-2050: climate projection including uncertainty estimates

Science Drivers
- Coupled Hydrological and carbon cycle multiscale projections
- Sea level rise projections: local processes, global impacts
- Terrestrial model calibrations using NGEE observations
- Predictive skill quantification for high-resolution simulations
- Water and Energy projections for stakeholders
- Short-lived species impacts: methane, aerosols, ozone