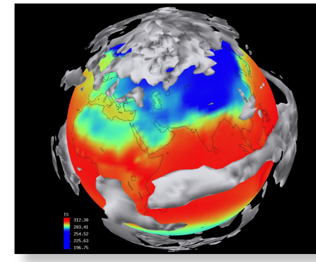
Multiscale methods for enabling scale-aware capability in CESM:

A SciDAC Climate Application

Bill Collins

Director, CLIMES and Head, Climate Sciences
Berkeley Lab and UC Berkeley
wdcollins@berkeley.edu

Simulating Climate Change @ Exascale

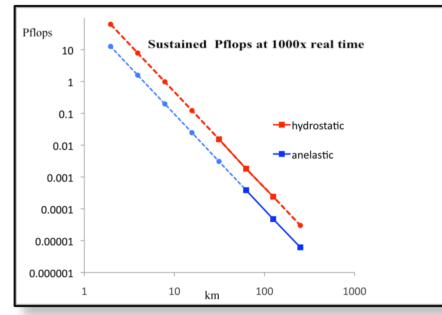


Drivers:

- What are the critical cloud controls on climate and the hydrologic cycle?
- What is the strength of the global carbon sink, and how will it change?

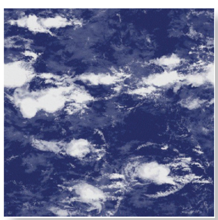
Exascale Impact:

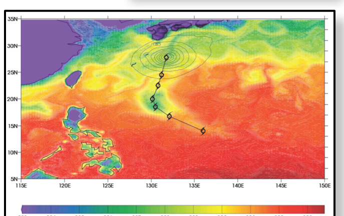
- **Reliable predictions of water and carbon cycles in warmer climates**



Current state:

- Our best petascale climate simulations are quite uncertain due to parameterization of clouds, convection, and ocean eddies.





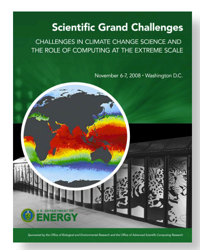
Need for exascale capability now:

- **Simulating clouds at their native scale for global climate is inherently an exascale problem.**
- **Modeling fully turbulent exchange of heat and gases between the atmosphere and ocean is an exascale problem.**

Transformational exascale capability:

- Robust climate models for early warning, adaptation, and mitigation

For further reading: Challenges in Climate Change Science and the Role of Computing at the Extreme Scale. DOE BER, 2009.



List of Priority Research Directions

- **How will local and regional water, ice, and clouds change with global warming?**
- How do the carbon, methane, and nitrogen cycles interact with climate change?
- How will the distribution of weather events, particularly extreme events, that determine regional climate change with global warming?
- What is the future sea level and ocean circulation?

Local and regional changes in water, ice, and clouds

Scientific and computational challenges

What are the critical cloud controls on climate?

What is the importance of motions and particle-scale processes that are still unresolved?

Potential scientific impact

These models will enable rapid progress in a wide variety of climate science issues (where clouds play an important role).

These models will bridge scales from weather to climate for the first time.

Summary of research direction

Development of global cloud resolving models and their application.

Potential impact on climate change sciences

These models will ultimately improve our ability to project changes in regional water cycles, a critical element of integrated assessment (Timescale: 5-10 years)

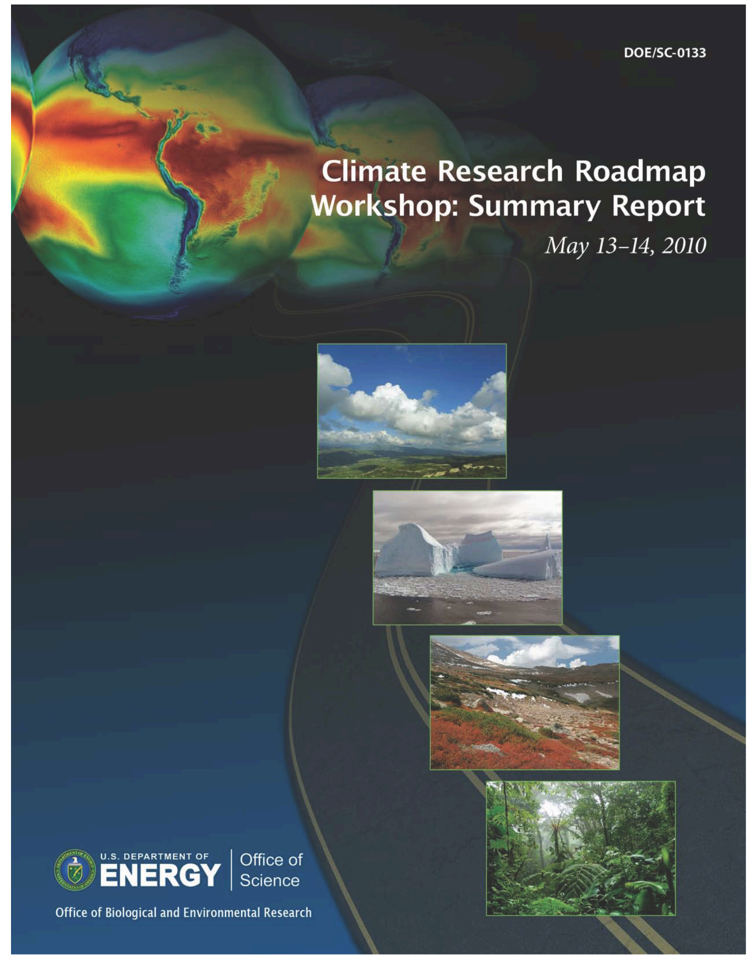
Cloud resolving models will be used to improve traditional climate models used for climate projection. (Timescale: 2-5 years)

Quantify impacts of water resources on energy production and use. (Timescale: 5-10 yrs)

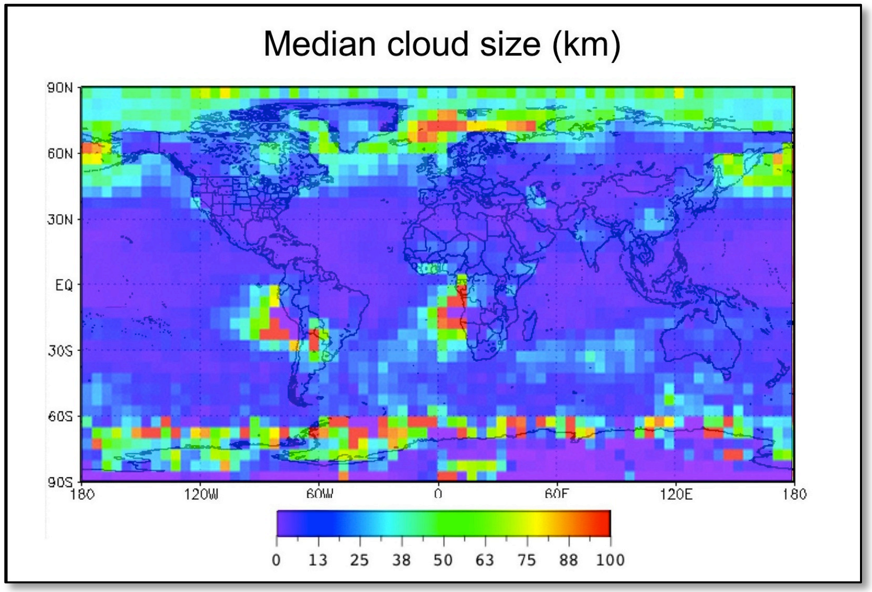
BER's Climate Research Roadmap

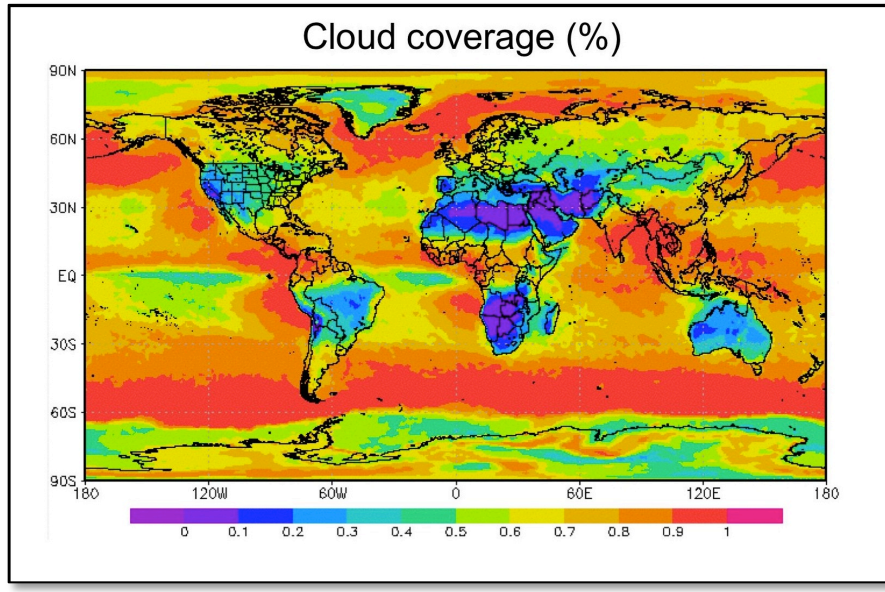
Desired outcome in atmospheric science:
Understand and quantify the interplay among aerosols, clouds, and climate and determine the mechanisms responsible for cloud feedbacks in order to improve the reliability of future climate change predictions, with particular attention to the impact on Earth's radiative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

Approach:
1. Aerosols and their interactions with clouds
2. <u>Cloud feedbacks</u>
3. <u>Improved strategies for high resolution modeling</u>



Clouds scales and model resolution

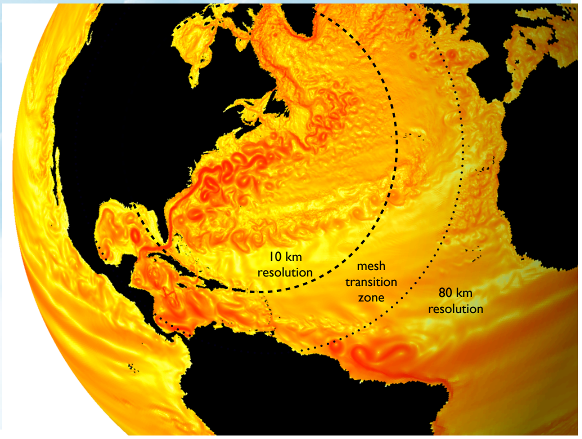




UHR AR5 AR4

Drivers for the project

- Many phenomena we want to simulate occur at the very small scales of clouds and ocean eddies.
- Two-way interactions are important for the organization and variability of the climate.
- Given cost of uniform ultra-high resolution, ***statically or dynamically refinable models*** could be a key experimental platform.



Requirements for the next generation of model physics

- Fidelity down to scales of key features of interest: cloud systems and ocean eddies
- Relaxation of usual parameterization assumptions:
  - *Ensembles:* Grid box may contain ~1 system, not >>1
  - *Scale separation:* Time steps and grid resolutions comparable to characteristic time and length scales of systems
  - *Equilibrium:* Due to scale "entanglement", sub-grid physics are not in equilibrium with boundary conditions imposed by resolved fields
  - *No memory:* Sub-grid systems will retain state across steps
  - *Scale awareness:* Physics needs to quasi-invariant to resolution
  - *Determinism:* Physics evolution is inherently stochastic.

Goals of the project

- Develop, validate, and apply multiscale models of the climate system based upon atmospheric and oceanic components with variable resolution.
- Exploit new variable resolution unstructured grids based on finite element and finite volume formulations developed by DOE.
- Integrate advances in time-stepping methods, grid generation, and automated optimization methods for next-generation computer architectures.

Multiscale Team

Principal Investigator:	**Bill Collins**
Science Team Leads:	
• *Atmosphere:*	**Steve Ghan**
• *Ocean:*	**Todd Ringler**
• *Computational Science:*	**Lenny Oliker**
• *Multiscale UQ:*	**Don Lucas**
Program managers:	**Dorothy Koch (BER) and Randall Laviolette (ASCR)**
Laboratory Staff and University Pis:	***LANL, LBNL, LLNL, ORNL PNNL, SNL, OSU, NCAR, UCLA, and UWM***

Connections to SciDAC Institutes

There are four SciDAC Institutes:

- **QUEST:** *Quantification of Uncertainty in Extreme Scale Computations*
- **SUPER:** *Institute for Sustained Performance, Energy and Resilience*
- **FastMATH:** *Frameworks, Algorithms and Scalable Technologies for Mathematics*
- **SDAV:** *Scalable Data Management, Analysis, and Visualization*

We will interact with 3 of these Institutes via liaisons:

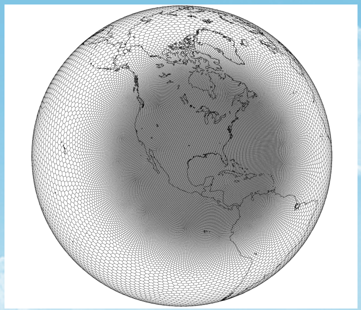
- **QUEST:** Bert Debusschere (SNL)
- **SUPER:** Lenny Oliker and Sam Williams (LBNL)
- **FastMATH:** Carol Woodward (LLNL)
- **Exec Council:** Bill Collins (LBNL)

Specific Task Areas

- **Multiscale modeling of the atmosphere**
  - *Clouds and convection (3 approaches)*
  - *Cloud and aerosol microphysics*
  - *Process integration*
  - *Verification, validation, and UQ*
  - *Experimental tests of the multiscale atmosphere*
- **Development and testing of multiscale ocean**
  - *Multiscale meoscale eddy parameterizations (4 stages)*
  - *Verification, validation, and UQ*
  - *Multiscale coupling of air-sea interactions*
- **Application of the multiscale Earth system model**

Implications for CESM software

- First and foremost, this is a ***physics*** project.
- We will use existing variable-resolution capabilities.
  - Potential wrinkle on horizon: adaptive mesh (CSSEF)



- Implications for the CESM software effort:
  - Introduction of multiscale capabilities onto CESM trunk
  - Collaboration to ensure ongoing support of these capabilities
  - Extensions to restart functions to save sub-grid states
  - Extensions to restart functions for stochastic processes
  - Support for GPU extensions for sampling of multivariate PDFs
  - Adaptation of Institute contributed code to CESM framework.

Computational Science by Year

1. Extract physics computational kernels and disseminate to SUPER and implement GPU enabled kernels within Trilinos.
2. Create performance models and prototype auto-tuners of the key physics kernels and optimize Trilinos solver within CAM dycore for many-core computing platforms.
3. Integrate best auto-tuned kernels into CESM, evaluate refinement techniques with smoother transition regions, and implement improved physics solvers using Trilinos.
4. Integrate best accelerated kernels into CESM, evaluate most promising refinement strategies in realistic CAM-SE simulations, and provide optimal nonhydrostatic solver options.
5. Evaluate performance of final kernel selections, optimize smoothing and refinement strategies using most promising scale aware parameterizations, and optimize nonlinear solver within nonhydrostatic CAM using many-core capable kernels.


Questions?