Petascale Modeling the Climate of the 20th and 21st Centuries: Recent Results

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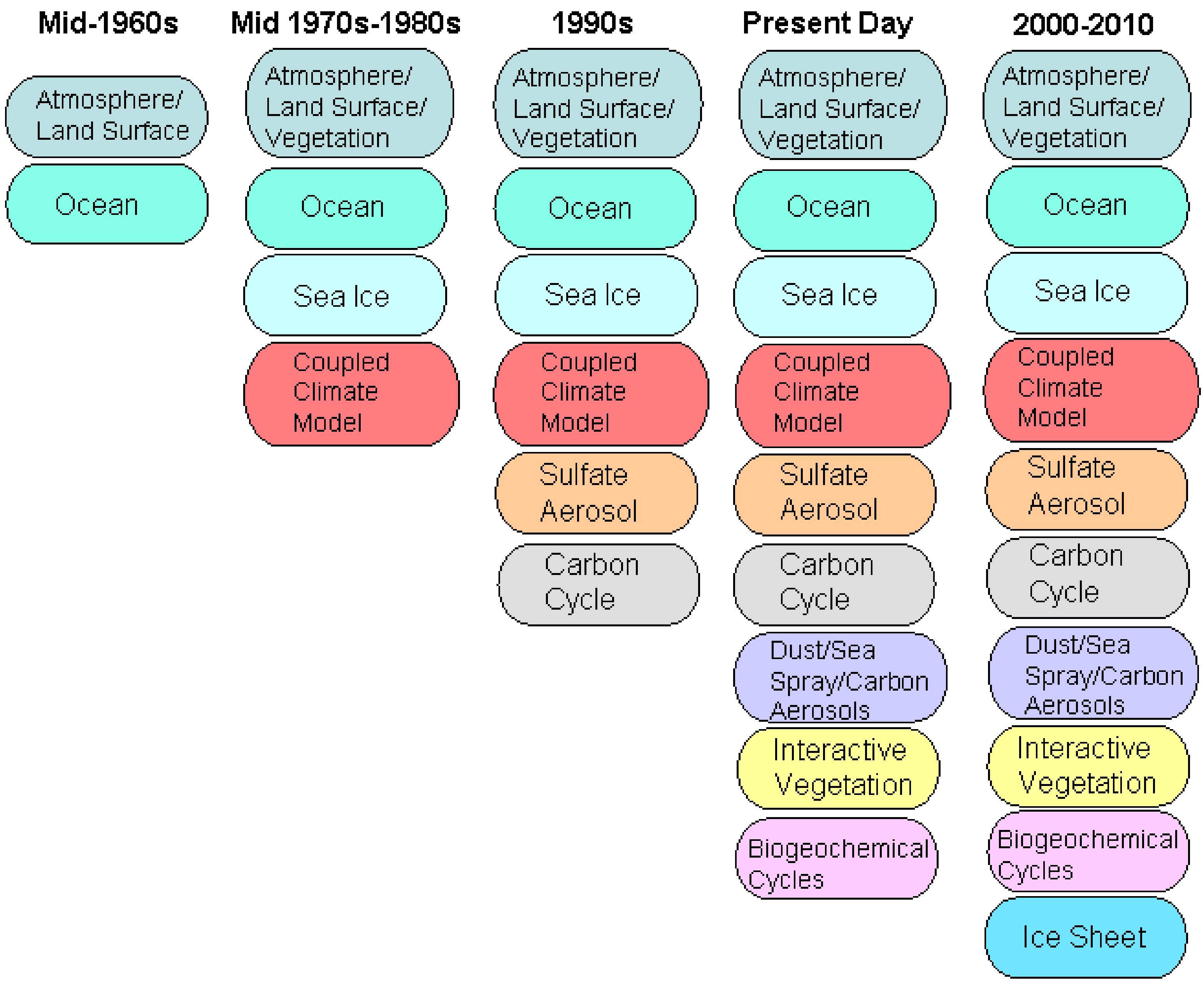
ORNL Climate End Station Objective

- **Purpose:** Deliver simulations that improve the scientific basis, accuracy and fidelity of climate models and perform climate change simulations that inform the both national and international science policy and contribute to DOE's Science Mission
- **Implementation:**
  - Develop, maintain and support the Community Climate System Model (CCSM) as the primary instrument of computational climate science.
  - Partner with institutions/projects that contribute high impact simulations
    - The CCSM project – Peter Gent (NCAR),
    - DOE SciDAC Consortium – John Drake (ORNL),
    - DOE COSIM project – Phil Jones (LANL),
    - DOE PCMDI project – David Bader (LLNL),
    - NASA Earth Sciences – Don Anderson (NASA Goddard),
    - DOE ORNL Climate Carbon Research Institute – David Erickson (ORNL), GaTech, Duke,
    - DOE PNNL Regional Climate Modeling – Steve Ghan (PNNL)
- **End Station Value Added**
  - Coordination among development and simulations
  - Priority setting in climate change research simulations
  - Sharing of code expertise, Developing scalable solutions

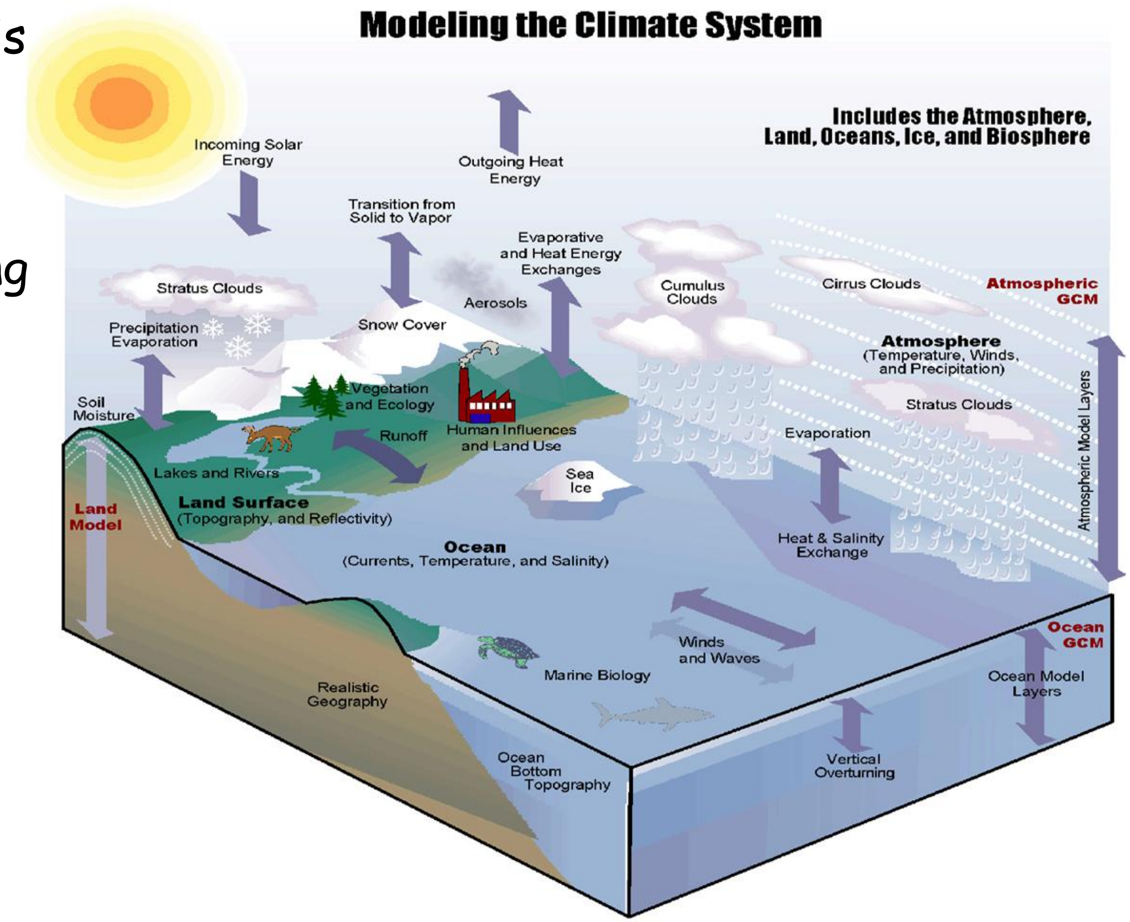
Timeline of Climate Model Development



The Earth Climate System

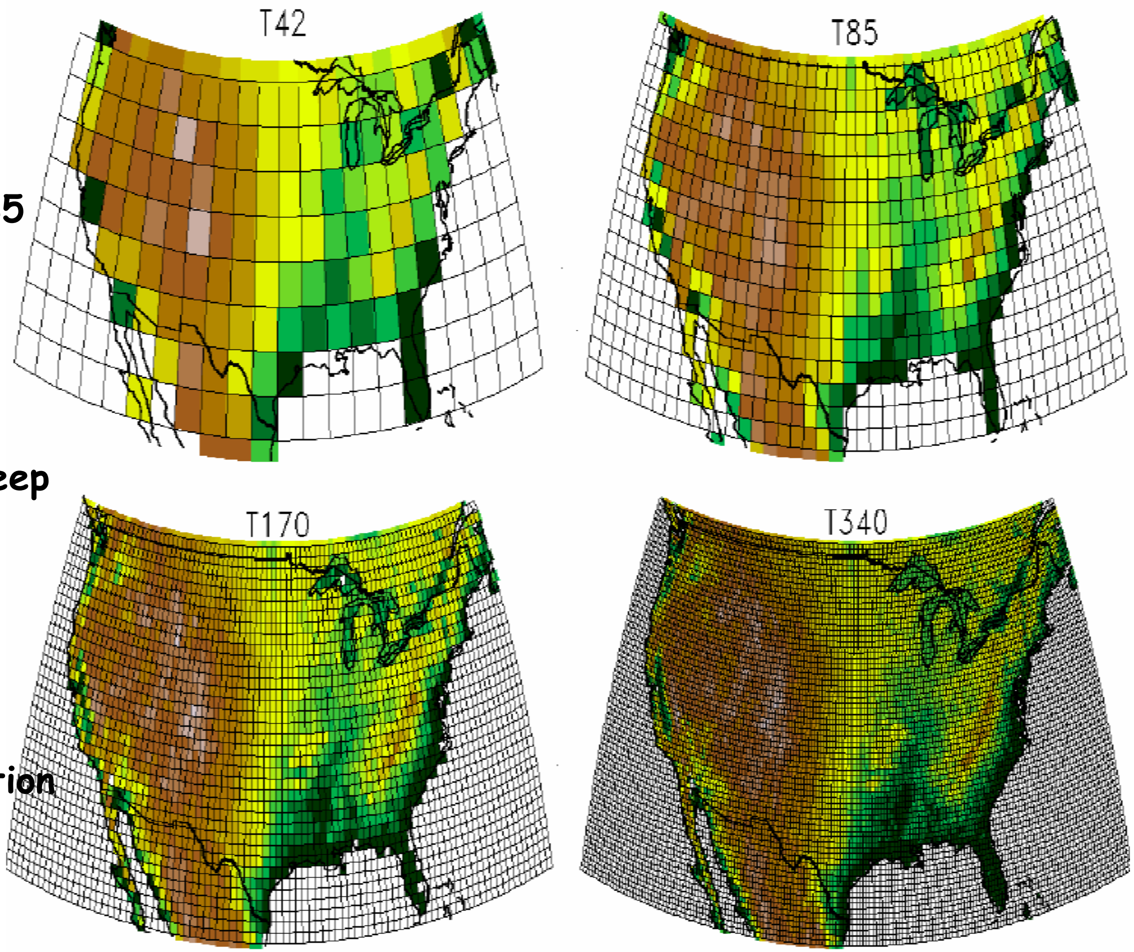
What scientific/engineering question(s) requires petascale computing

The Grand Challenge problem is to predict future climates based on scenarios of anthropogenic emissions and changes resulting from options in energy policy



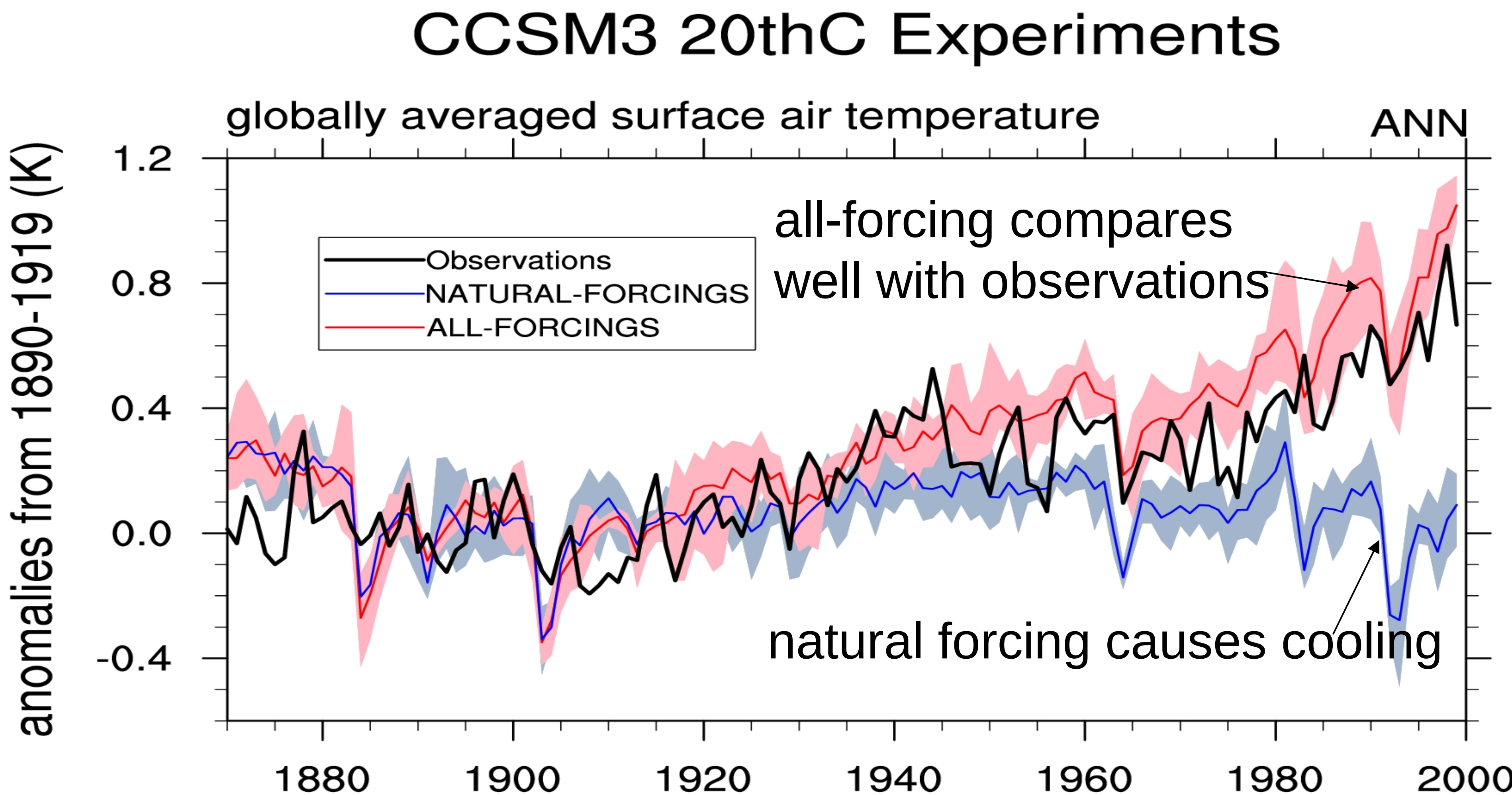
Climate-Science CES Development & Grand Challenge Team
Leadership Computing Enables Aggressive Milestones

- FY06 Milestones
  - High resolution ocean and sea ice , POP2 and CICE
  - High resolution atmosphere model bias studies,
  - Biogeochemical intercomparison simulations from C-LAMP
  - Climate Change scenarios stabilization with CCSM3.0 at T85
- FY07 Milestones
  - Bias studies with high resolution atmosphere/ocean coupling,
  - Dynamic ecosystem feedback simulation,
  - High resolution ocean THC and deep water formation,
- FY08 Milestones
  - Fully coupled physical climate at high resolution
  - Chemical coupling of climate and ecosystems
  - Climate sensitivity of high resolution coupled model.



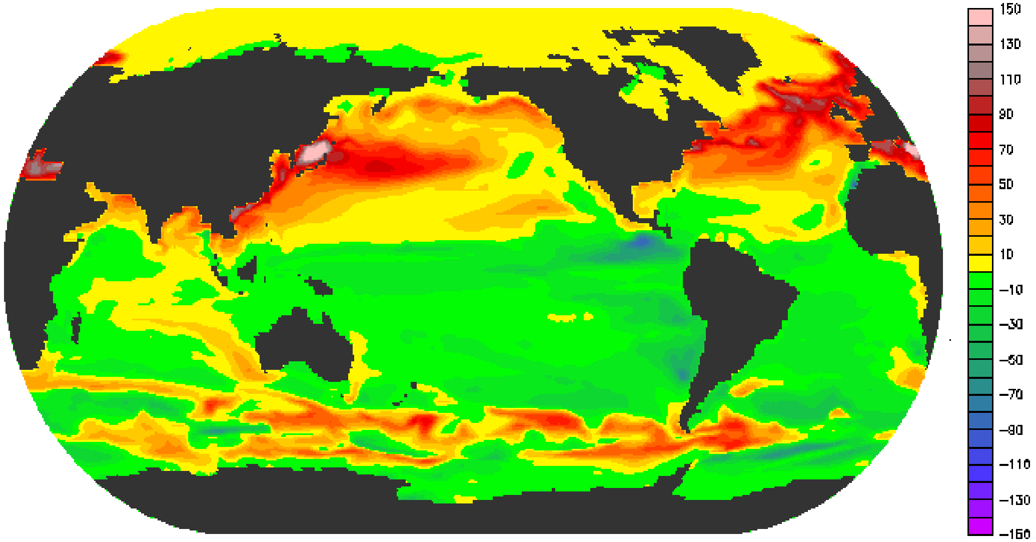
High Resolution (horizontal) 0.1^o World Ocean Simulations

Detection of Climate Change: Natural Forcings versus Natural +Anthropogenic Forcing



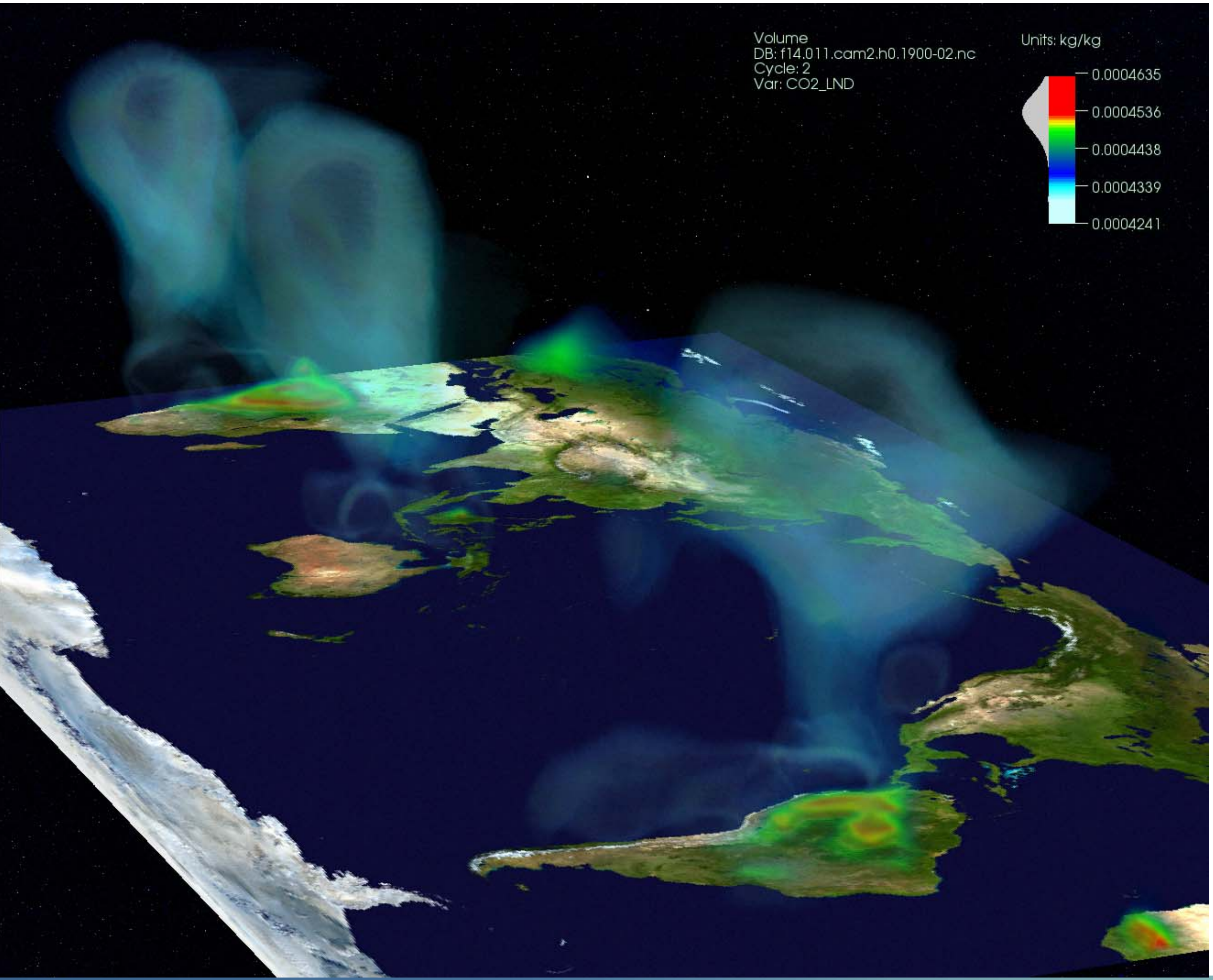
Earth System Model Prototype

- Flux of CO2 into the ocean
- Biogeochemistry development code
  - Atm + Mozart chemistry
  - Ocn + DML ecosystem + trace gases
  - Land + CASA' carbon
  - Modified flux coupler



(courtesy M. Maltrud)

Carbon Land Model Intercomparison (C-LAMP)



(courtesy J. Daniel)

- What are the relevant processes for carbon in the next version of the CCSM?
- Comparison of CASA', CN, and IBIS

Software Stack

What software must be available on the system for you to be successful

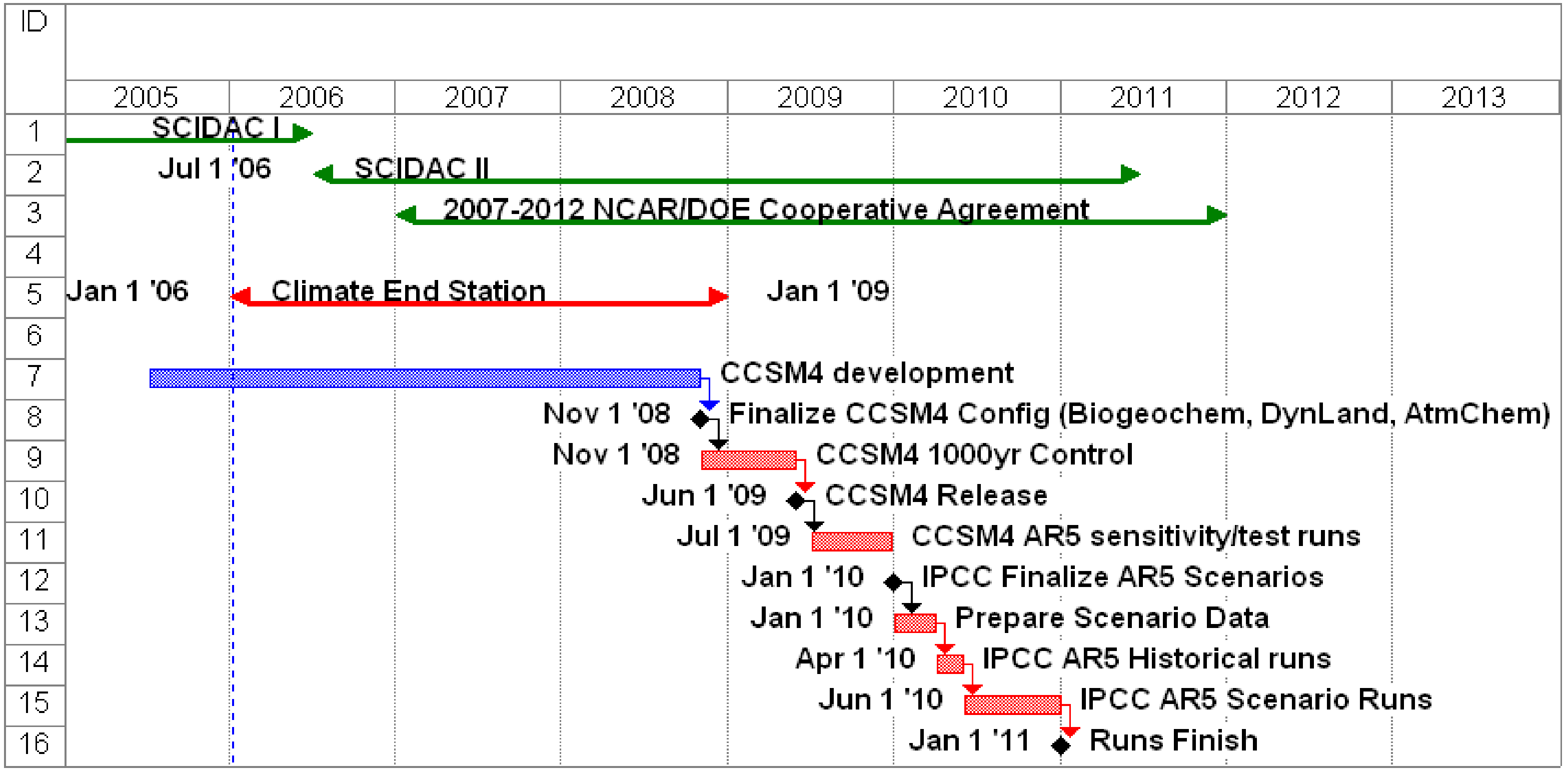
- Multiple binary launch (MPMD)
- MPI and OpenMP (hybrid parallelism)
  - Fast, bit-for-bit collective operations
  - Fault detection and recovery
- F90, C, C++ optimizing compilers
- Stable OS and programming environment

CCSM enabling technologies

- Utility Layer Software
  - Model Coupling Toolkit (MCT – Argonne)
  - Components and Communicators (MPH-Berkeley, CCA)
  - Earth System Modeling Framework (ESMF - NASA)
- Systems and Tools
  - Earth System Grid (ESG – Livermore/NCAR/ORNL/LANL)
  - Performance tools (e.g. Tau – PERC Project)
  - Parallel I/O (pNetCDF – SDM Project)
  - Source code version control (Subversion)
- Techniques
  - Iterative techniques: PCG, N-K, AMG
  - Grid systems: icosahedral, cubed sphere, AMR
  - Discretizations: spectral, finite volume, spectral element, DG
  - Formulations: hydrostatic, non-hydrostatic, lagrangian and flux form semi-lagrangian

Climate End Station, CCSM Development and IPCC AR5: THE BIG PICTURE

- CES FY06 Allocation
  - 2 million CPU hrs on Phoenix Cray X1E
  - 3 million CPU hrs on Jaguar Cray XT3
- Need to coordinate 7 different CES subprojects leading up to CCSM5



In last week's SCIENCE magazine!
Should we "Geoengineering the Planet"?
Earth System Models can help sort out options!

ATMOSPHERIC SCIENCE

Pollute the Planet for Climate's Sake?

The source of the proposal was almost as remarkable as the idea itself. In the August issue of *Climatic Change*, Paul Crutzen, who won the Nobel Prize for helping work out the chemistry of ozone destruction in the stratosphere, resurrected an oft-disparaged suggestion: Create a global haze by spewing megatons of sulfurous debris into the stratosphere to shade the planet and rein in greenhouse warming. "A few years ago, I would have said, 'I'm not touching that,'" says the Max Planck Institute for Chemistry researcher. Now, however, he finds the "grossly disappointing international political response" to global warming's threat so disturbing that the notion of deliberately contaminating the stratosphere looks less and less crazy.

Bad idea, respond some climate scientists. It would be applying a Band-Aid to the symptom while continuing to stoke the problem with ever-increasing greenhouse gas emissions. Best not even to talk about it. Worth looking at, say others. Given the surprises that may be lurking in the greenhouse, desperate countermeasures could come in handy. Thanks to Crutzen's stature, this scientific and ethical debate is blossoming as the climate community begins to take a hard look at geoengineering climate.

Supporters of at least studying the idea seem to have some momentum for now. "Crutzen's paper created some sort of phase change, making geoengineering a respectable topic of conversation," says climate modeler Kenneth Caldeira of the Carnegie Institution Department of Global Ecology at Stanford University.

Geoengineering as a fix for global warming has been a topic of usually sotto voce conversation since the 1970s, when the Soviet climatologist Mikhail Budyko suggested Earth could be cooled by adding tiny sunlight-reflecting particles to the stratosphere. Nature soon served up a couple of striking examples of how it might be done when the volcano El Chichón erupted in 1982 and Mount Pinatubo erupted in 1991. The long-lived stratospheric debris of Pinatubo—water droplets laced with sulfuric acid derived from the volcano's sulfur—reflected enough sunlight back into space to cool Earth on average 0.5°C for a year or two following the eruption. That's about the size of the warming of the past century.

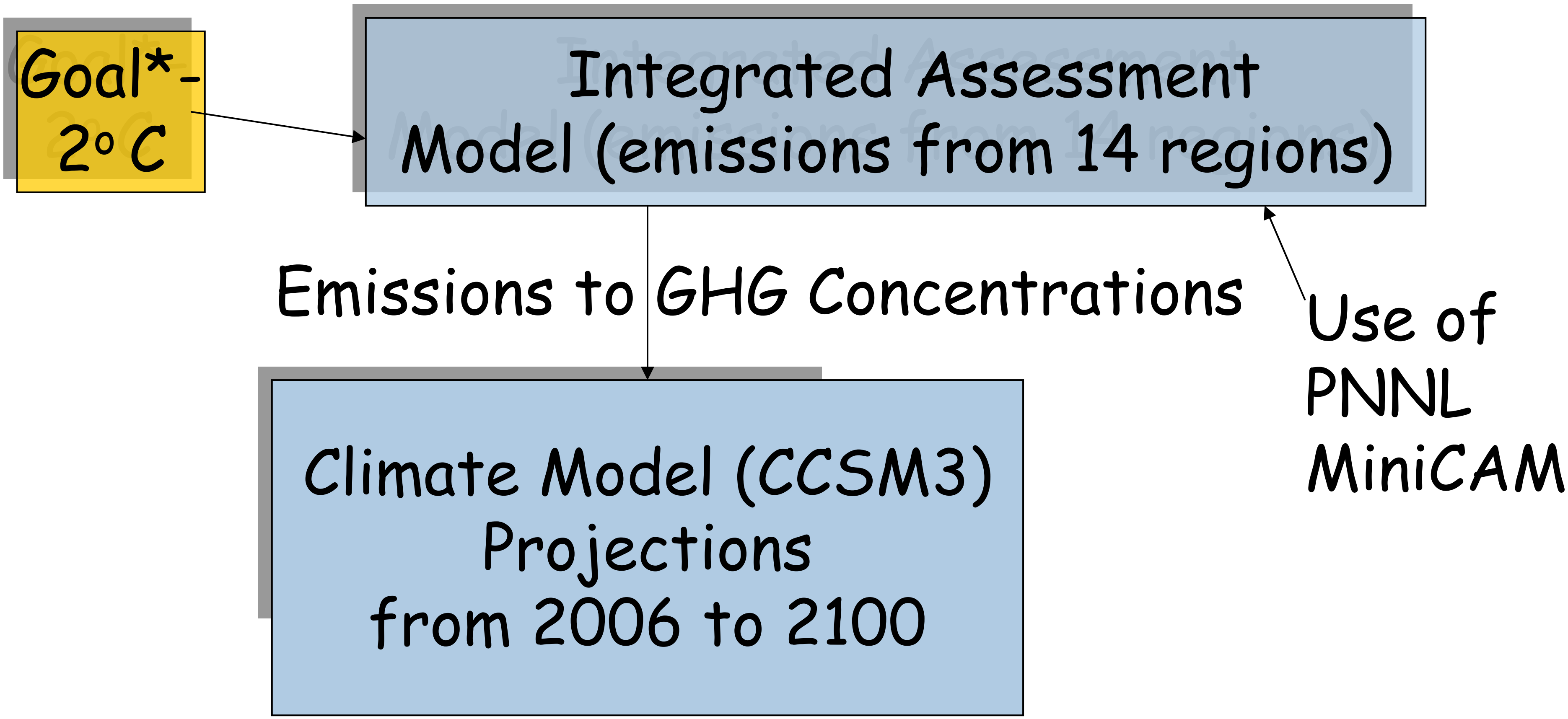
Pulling off a "human volcano" to counteract global warming would take some wherewithal. Pinatubo put up 10 million tons of sulfur, most of which fell out of the stratosphere within 2 or 3 years. So humans looking to cool the greenhouse by stratospheric shading would have to send millions of tons of sulfur tens of kilometers into the air every year, perhaps century after century, in order to renew the continually depleted shield of haze. The resulting acid rain would be minor compared to current levels, say proponents.

People have discussed delivery methods from balloons, big guns, and giant planes. To ease the burden of lifting megaton masses, the late Edward Teller—father of the hydrogen bomb and "Star Wars" missile defense advocate—proposed substituting more efficient reflectors for sulfur, something metallic and perhaps engineered like tiny retroreflectors.

A volcanic chill. Humans might loft sulfur into the stratosphere to counteract global warming; Mount Pinatubo did in 1991.

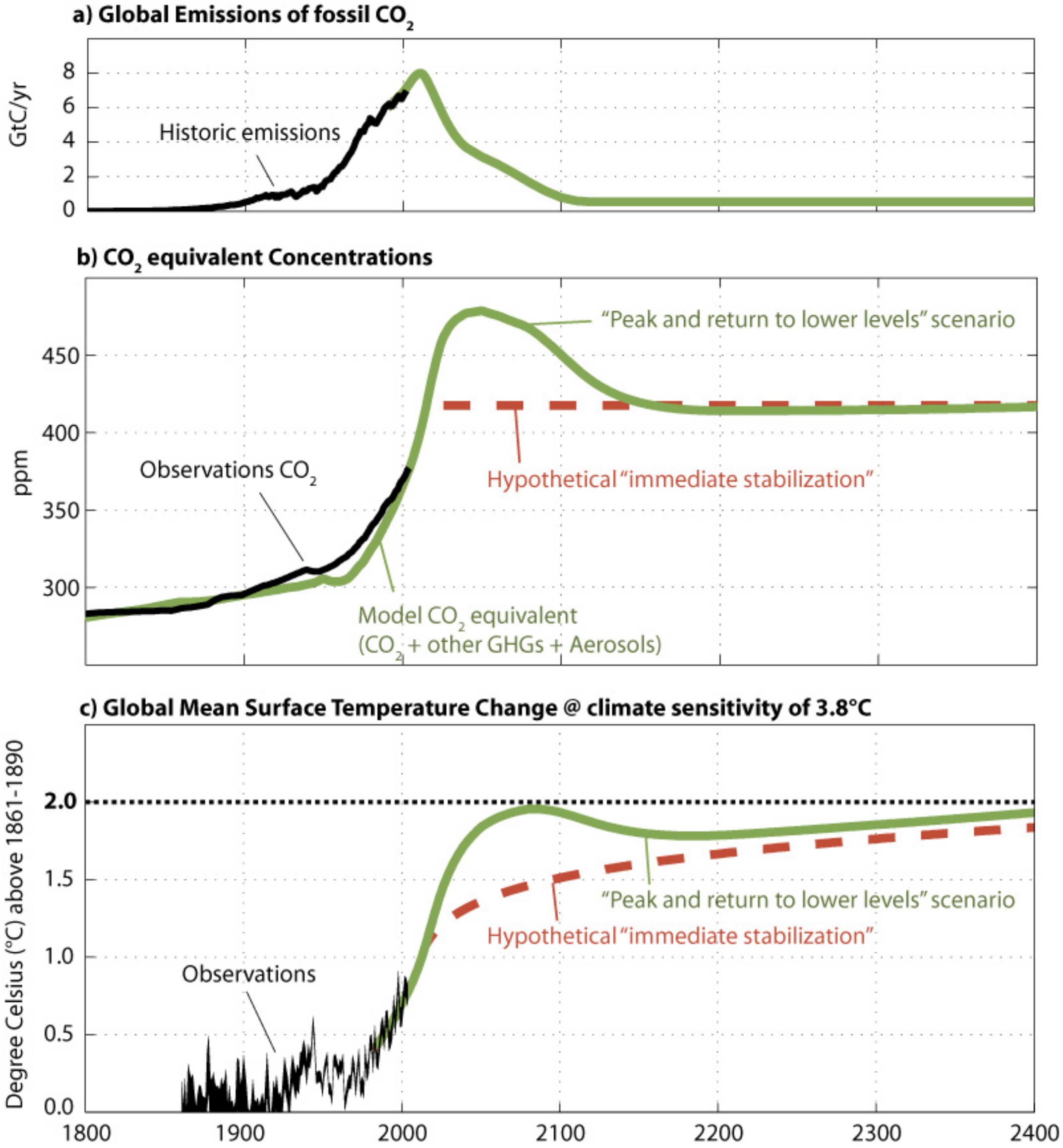
CREDIT: BULLIT MARQUEZ/AP PHOTO

Next Steps to Climate Change using Low Emission Projections



*Goal: Global Mean Surface Temperature Change from Pre-industrial to 2100.

Overshoot Stabilization Scenarios



A short overshoot of atmospheric CO_2 might be compatible with the 2°C target.

(Meinshausen et al., realclimate.org)

Summary

- DOE SciDAC2 is collaborating with NSF and NASA projects to build the next generation Earth System Model
- The NLCF Climate End Station provides a major portion of the development and climate change simulation resources
- Scalability and Extensibility are required for petascale science applications
- Distribution of Data will be accomplished by the DOE Earth System Grid*

*Several Petabyte range

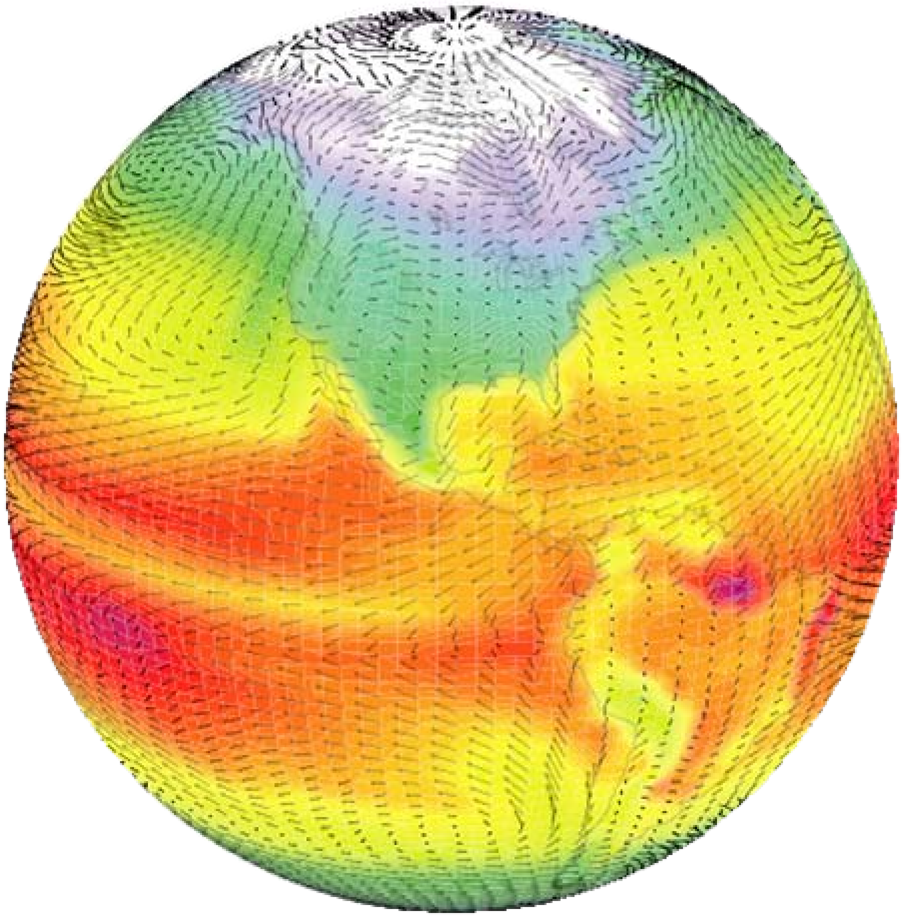
Acknowledgements

- Additional Collaborators at ORNL, PNNL, LANL, LANL, NASA, NCAR, Georgia Tech, Duke University, and many other university scientists and computational experts.

The end

Coupled Climate Modeling

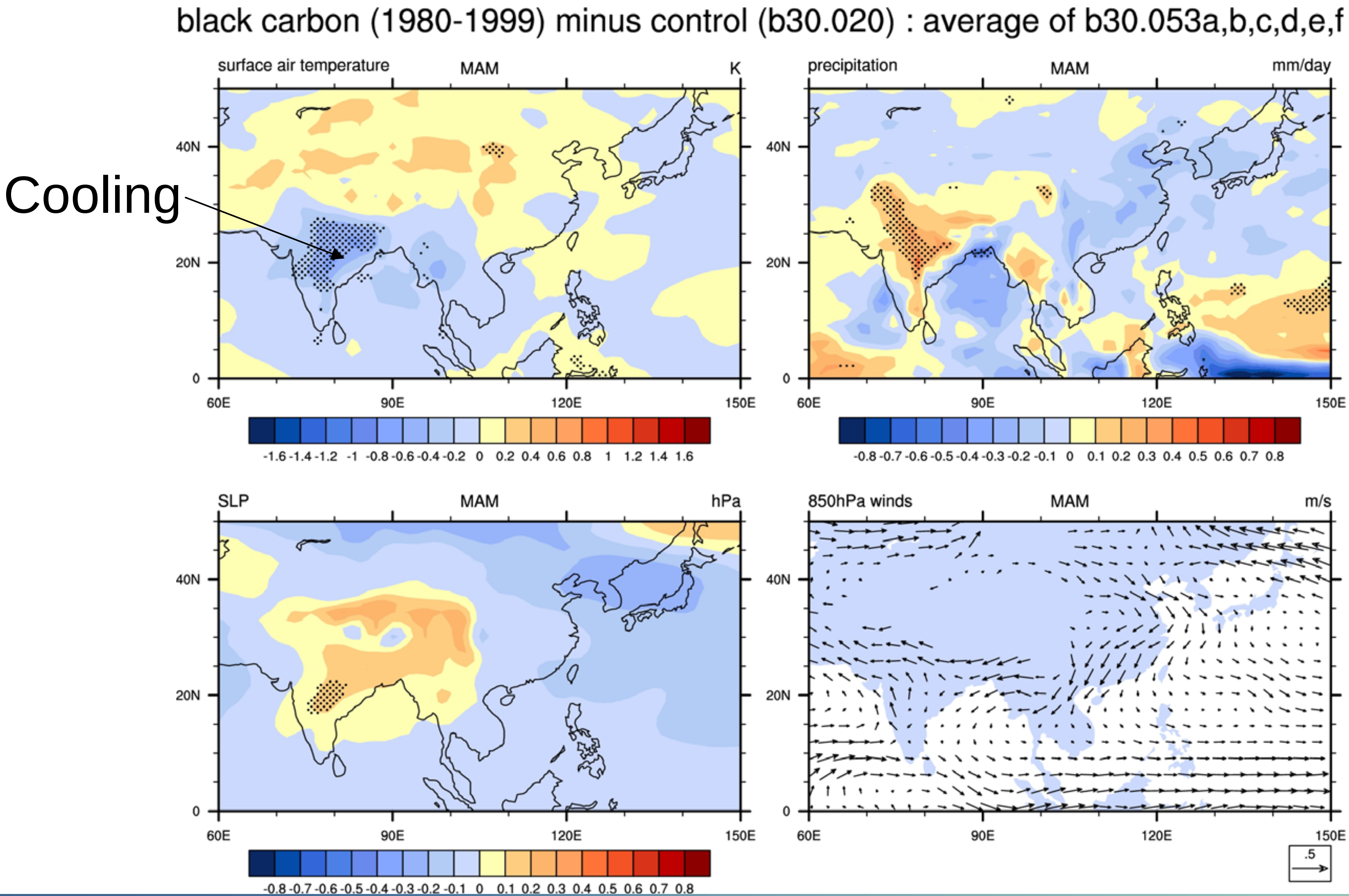
- Confidence in modeling the physical climate system does not extend to modeling the biogeochemical coupling
- Using observational data to validate and constrain the process models for terrestrial carbon cycle and atmospheric aerosols
- Extending cryosphere to include ice sheets.



Why is it important?

- To the science/engineering community
  - Discoveries of feedbacks between ecosystems and climate
  - Fundamental science of aerosols effect in the atmosphere
  - Advances in modeling and simulation science for climate prediction
- To the public
  - US and International Energy policy
  - Contribution to international assessments of climate change and its causes such as the Intergovernmental Panel on Climate Change (IPCC) Assessment

What is the role of carbon aerosols on the winter Indian Monsoon?



How do you know petascale computing is required ?