# The Brief History and Future Development of Earth System Models: Resolution and Complexity

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**National Center for Atmospheric Research**

NERSC Lecture Series at Berkeley Lab
May, 2014

NCAR

U.S. DEPARTMENT OF ENERGY
Office of Science

# Overview

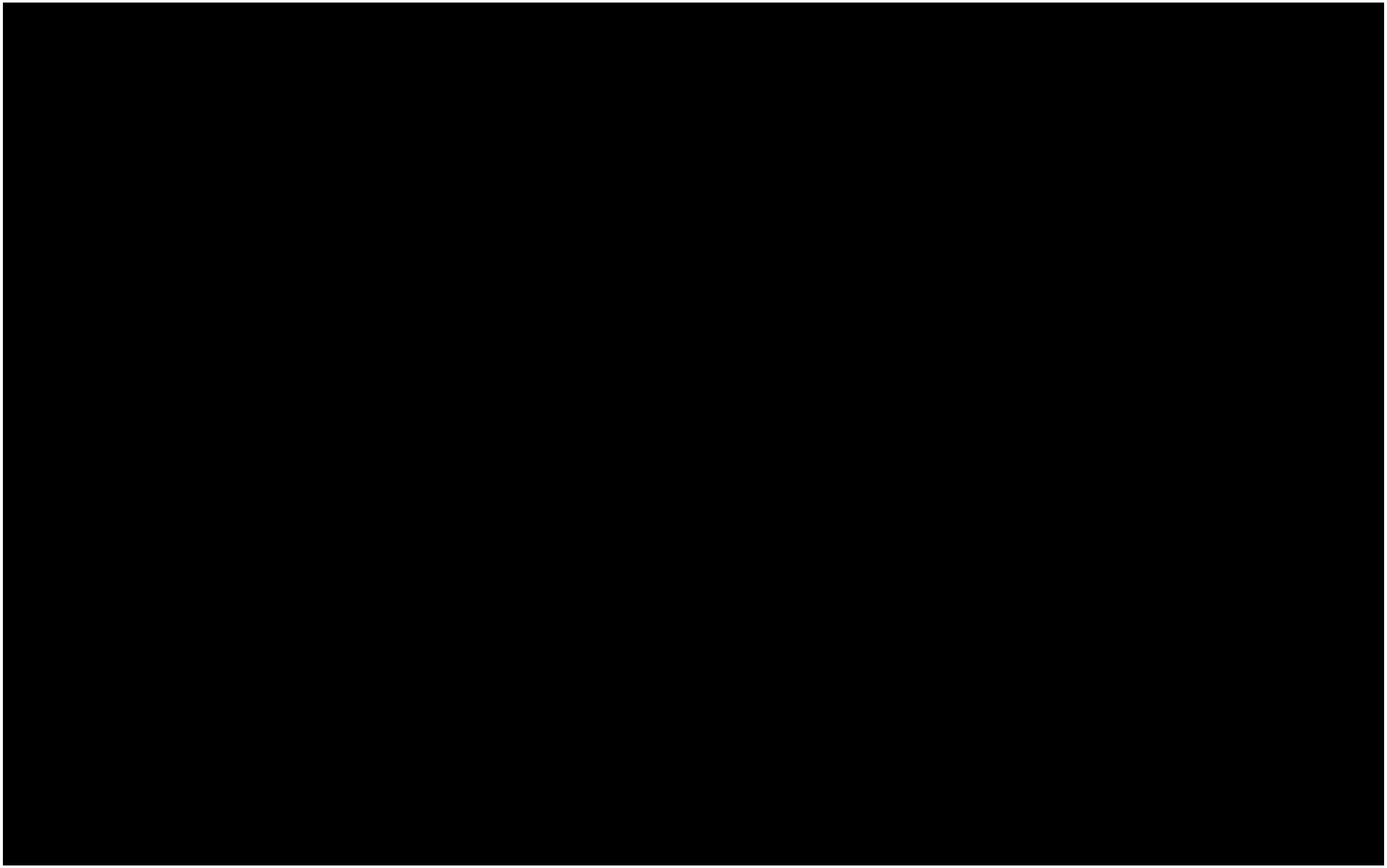
- Brief history of climate modeling
- Brief discussion of computational methods
- Environmental Justice connected to climate change
- Behind the scenes White House origin of the U.S. Global Change Research Program (USGCRP)
- The future of the USGCRP and National Climate Assessment

**The next two NASA satellite videos give insight to how the climate is changing and the interaction of vegetation on the carbon cycle.**

Credit to the NASA Aqua instrument:
Tom Pagano and colleagues at JPL


Mauna Loa, Hawaii
(MLO)

# The atmospheric carbon dioxide and vegetation connection!

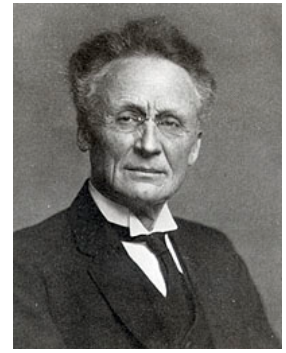


# The Climate and Earth System Modeling Story

# Laws of Physics, Chemistry, and Biology

- Equations govern the dynamics of atmosphere, ocean, vegetation, and sea ice
- Equations put into a form that can be solved on modern computer systems
- Physical processes such as precipitation, radiation (solar and terrestrial), vegetation, boundary transfers of heat, momentum, and moisture at earth's surface are included
- Forcings: GHGs, Volcanic, Solar variations

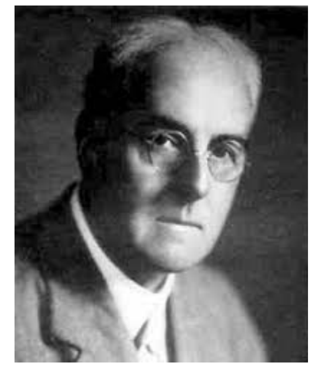
# Mathematical equations (known since 1904)



Eqs. of Momentum

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right) v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial \lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right) u = -\frac{1}{\rho a}\frac{\partial p}{\partial \phi} + F_\phi$$



Hydrostatic

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

Conservation of mass

$$\frac{\partial \rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial \lambda}(\rho u) + \frac{\partial}{\partial \phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

First law of thermodynamics

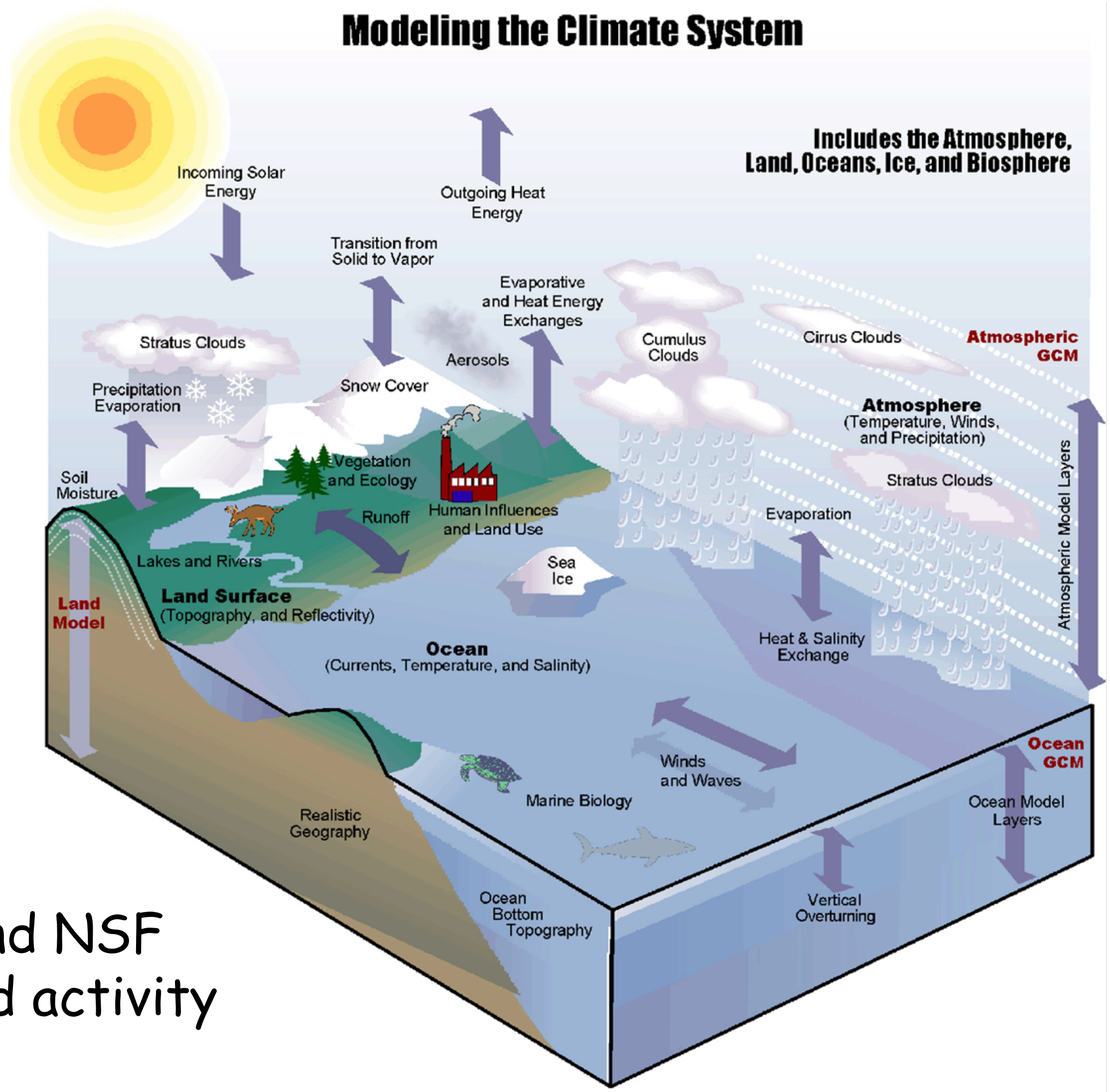
$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

Gas law

$$p = \rho R T$$

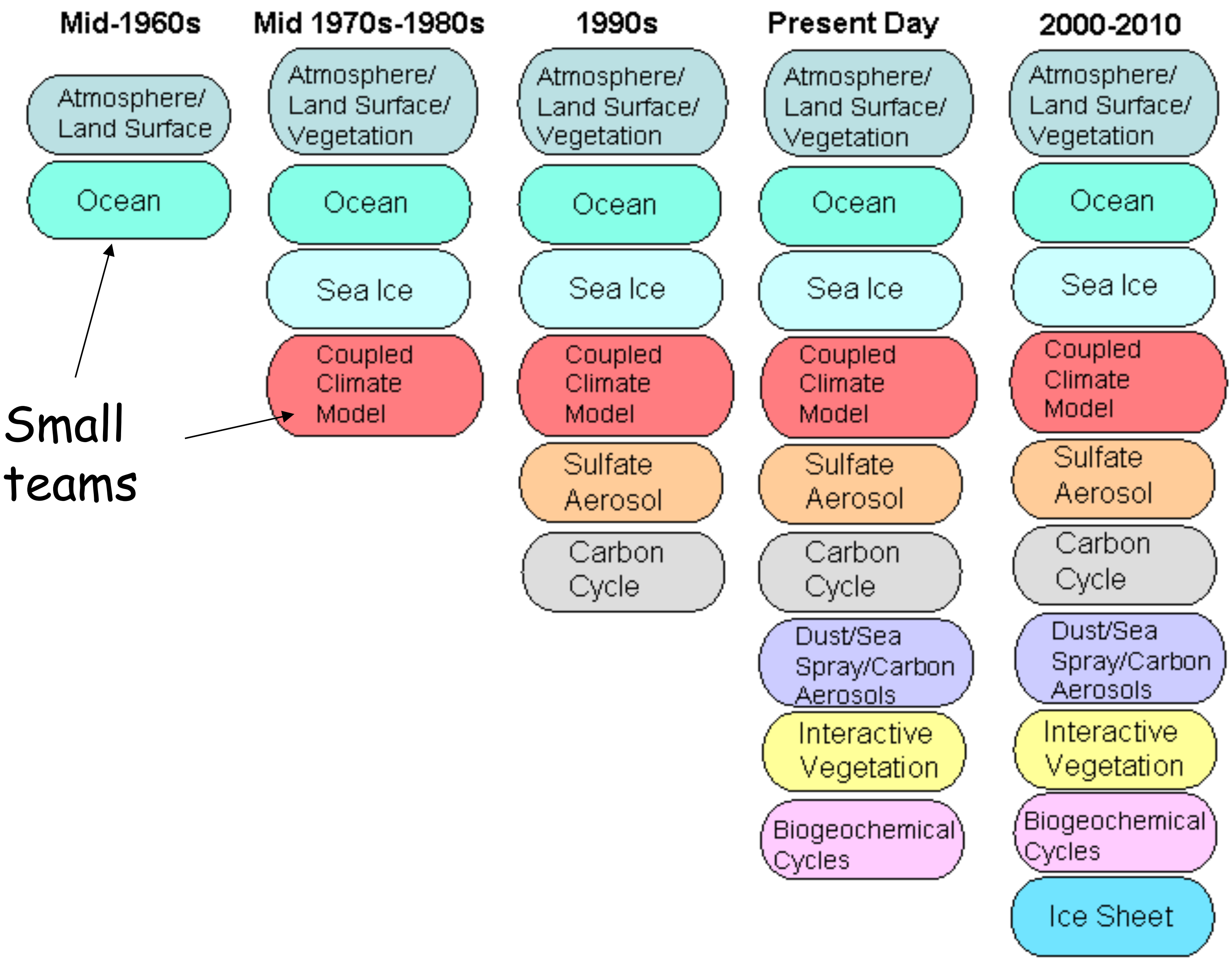
$(u, v, w, \rho, p, \text{and } T)$,

# The Community Earth System Model (CESM) is becoming more complete



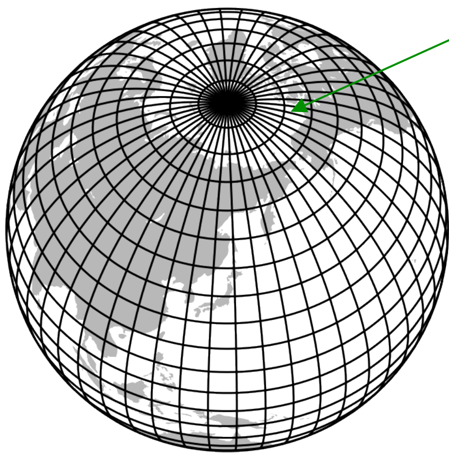

A DOE and NSF supported activity

# Timeline of Climate Model Development



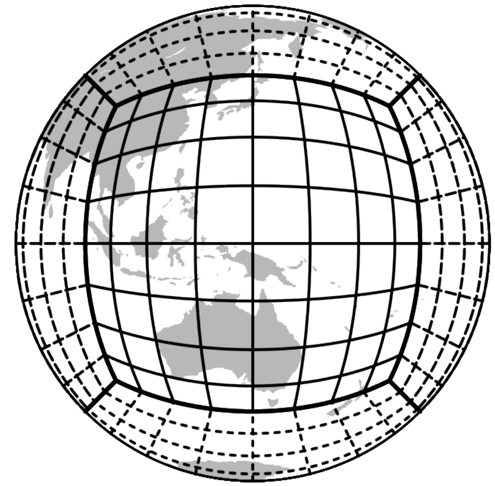
# Atmospheric Grids

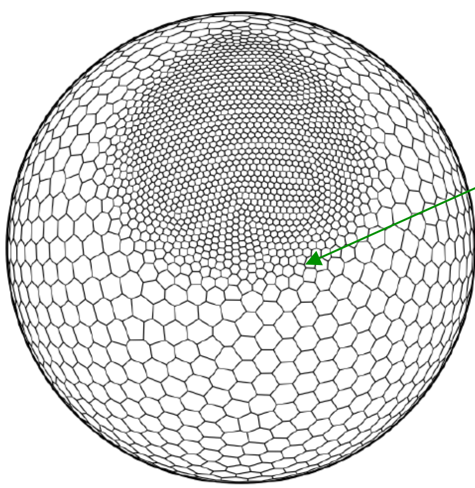
LATITUDE-LONGITUDE GRID



Problem near the poles where longitudes converge

CUBED SPHERE GRID

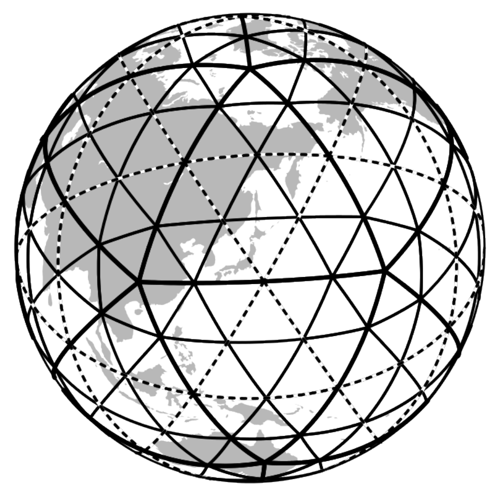




Regional focus

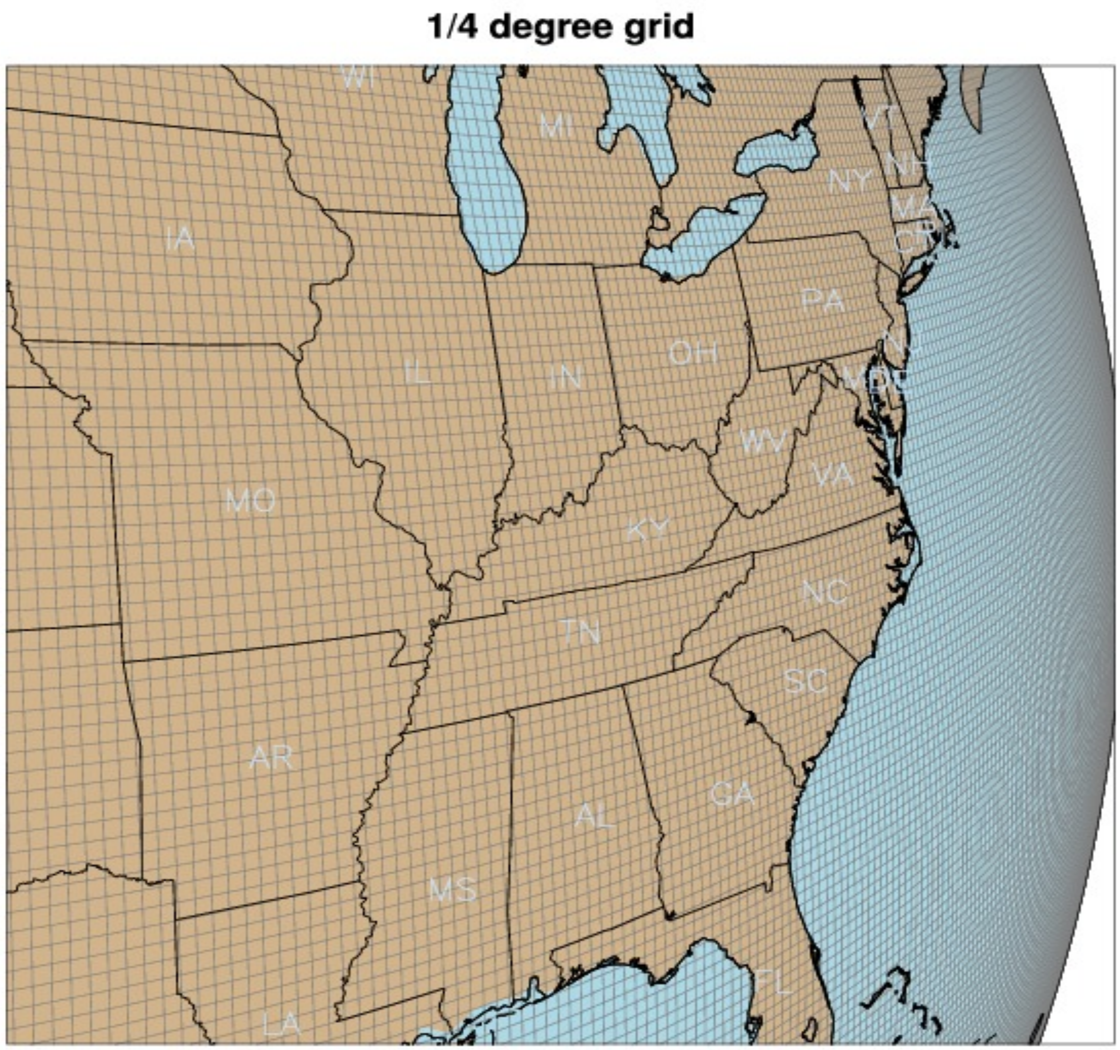
Figure V.1. A variable resolution grid based on a Spherical Centroidal Voronoi Tesselation.

SPHERICAL GEODESIC OR ICOSAHEDRAL GRID



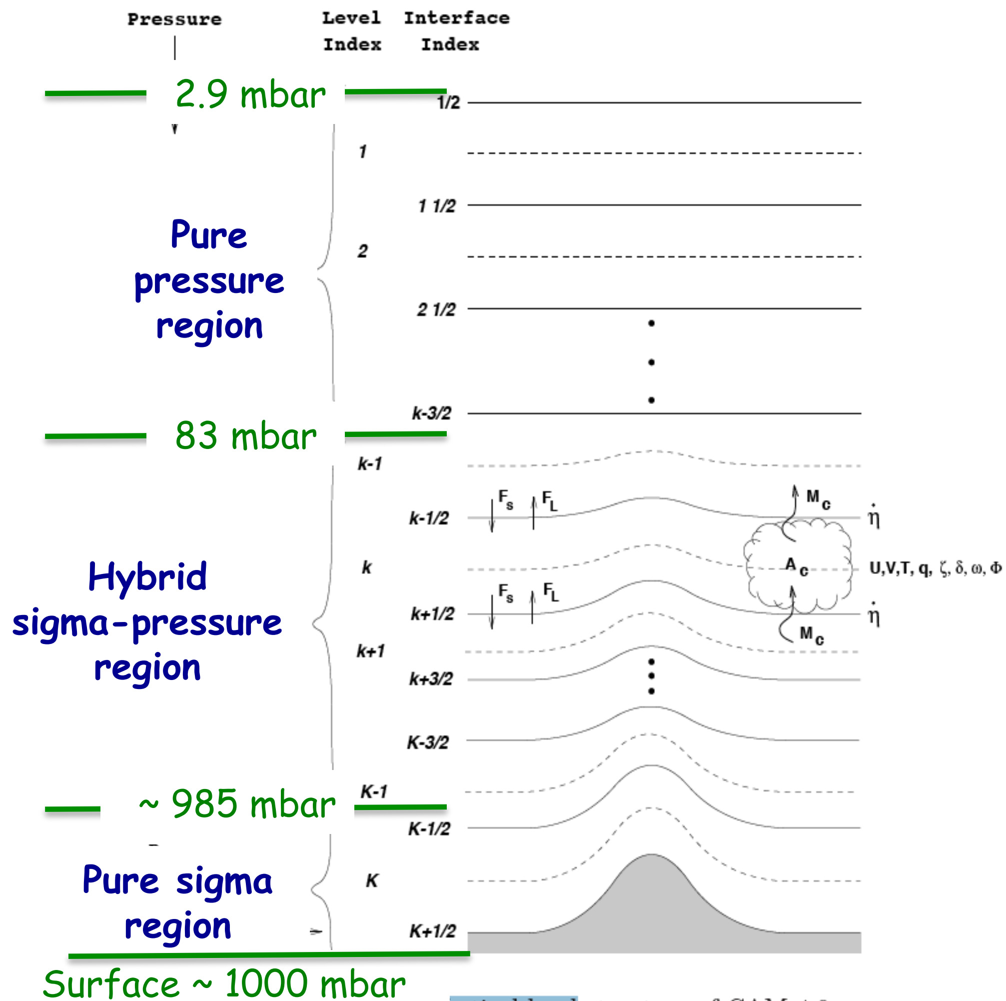
From C. Hannay, NCAR

Part of the global grid (25 km) for the next IPCC simulations

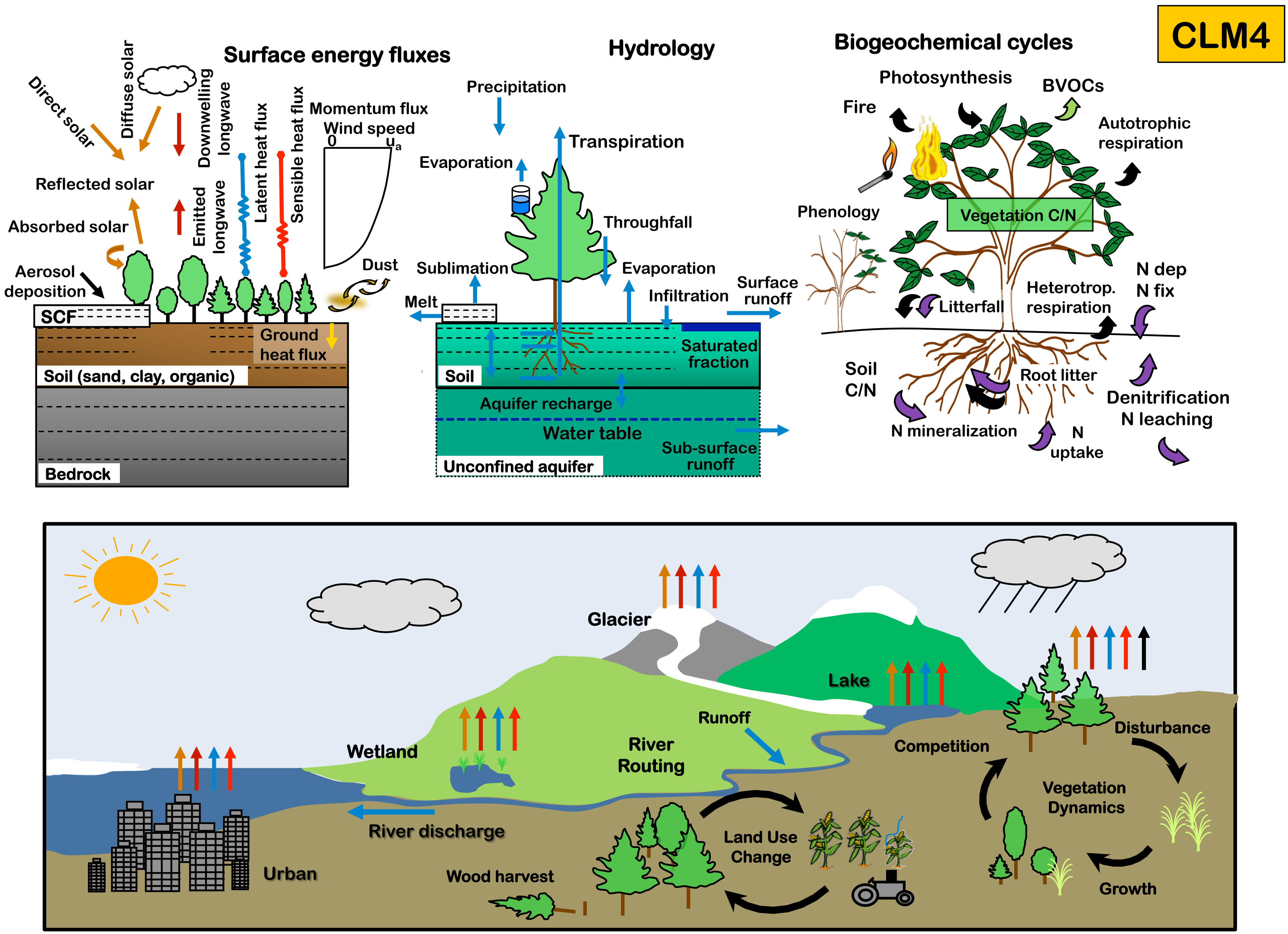


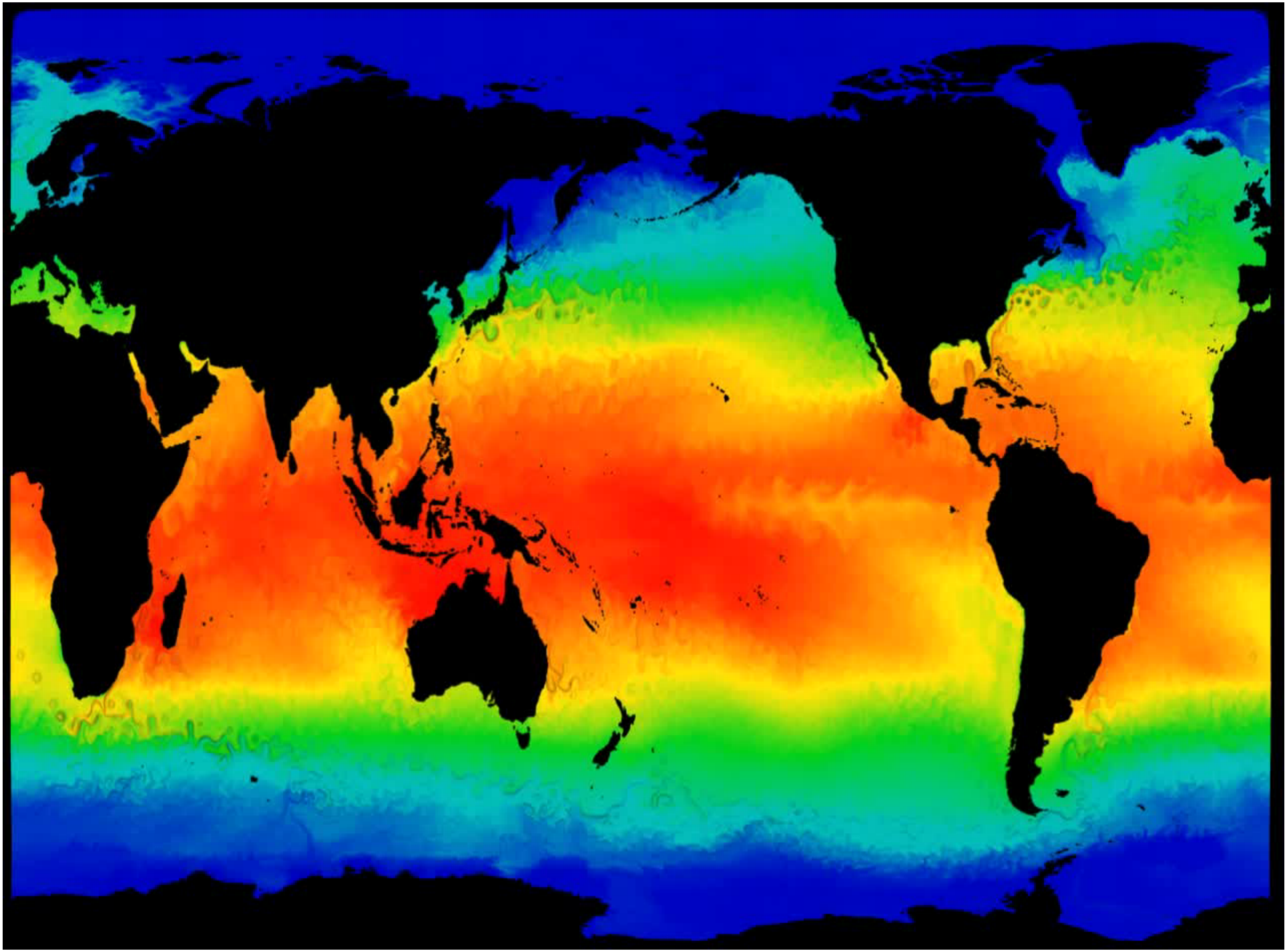
# Vertical Grid

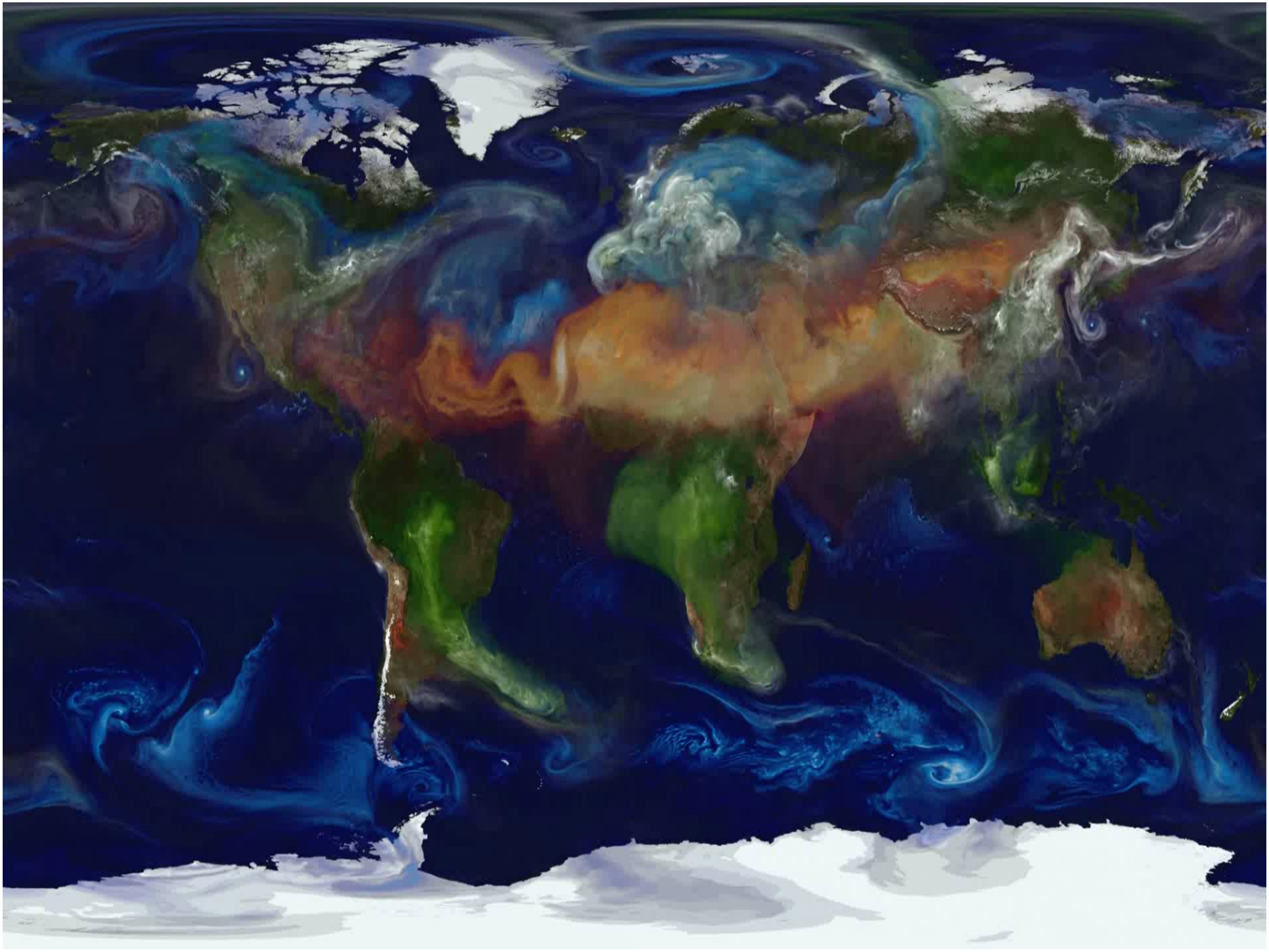
- Vertical resolution is also important for quality of simulations
- Levels are not equally spaced (levels are closer near surface and near tropopause where rapid changes occurs)
- In CAM: "hybrid" coordinate
  - bottom: sigma coordinate (follows topography)
  - top: pressure coordinate
  - middle: hybrid sigma-pressure



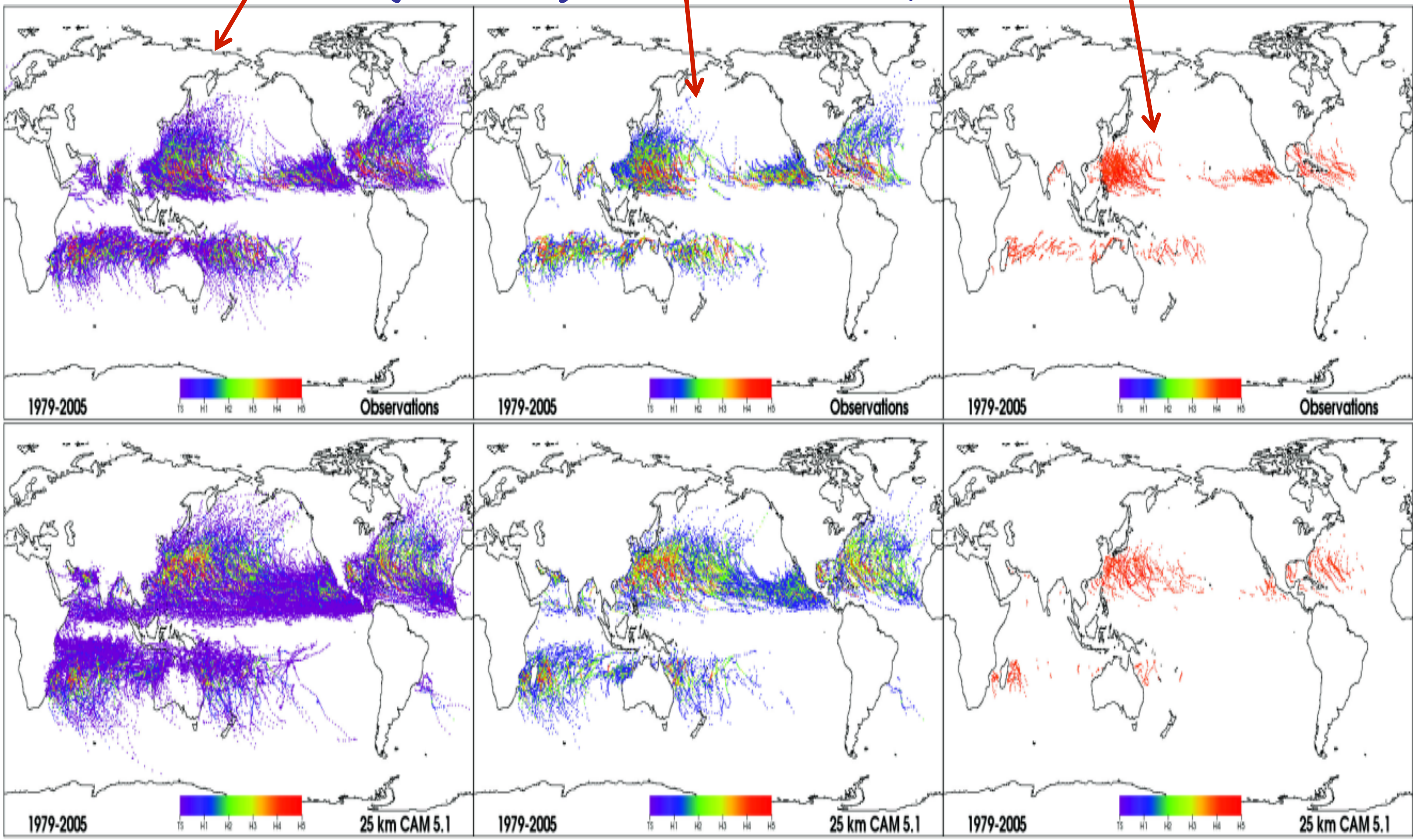
Vertical level structure of CAM 4.0


CLM4
Surface energy fluxes
Hydrology
Biogeochemical cycles
Direct solar
Diffuse solar
Downwelling longwave
Reflected solar
Absorbed solar
Emitted longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
0
$u_a$
Dust
Aerosol deposition
SCF
Ground heat flux
Soil (sand, clay, organic)
Bedrock
Precipitation
Transpiration
Evaporation
Throughfall
Evaporation
Sublimation
Infiltration
Surface runoff
Melt
Soil
Saturated fraction
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
N dep
N fix
Heterotrop. respiration
Litterfall
Soil C/N
Root litter
Denitrification
N leaching
N mineralization
N uptake
Glacier
Lake
Wetland
Runoff
River Routing
Competition
Disturbance
Vegetation Dynamics
Growth
River discharge
Urban
Land Use Change
Wood harvest



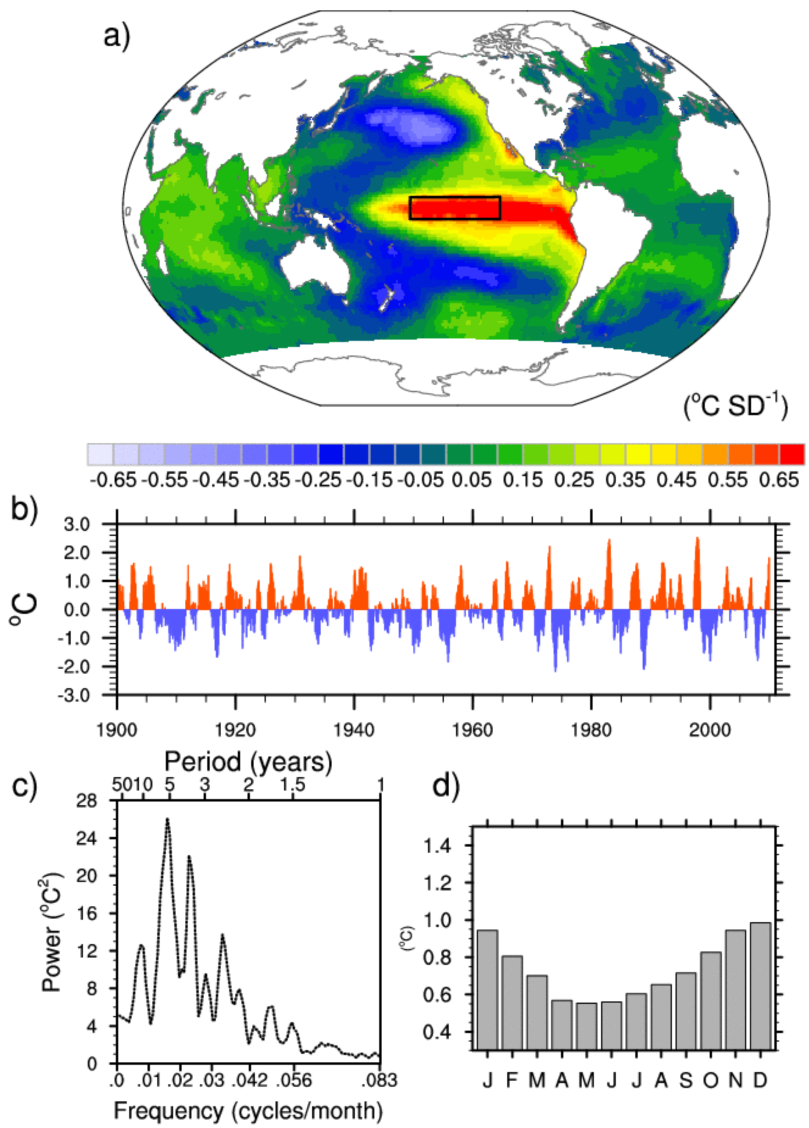


# Tropical storms, hurricanes, and intense hurricanes for high resolution (25 km) atmospheric model(CAM5) M. Wehner, DOE LBL

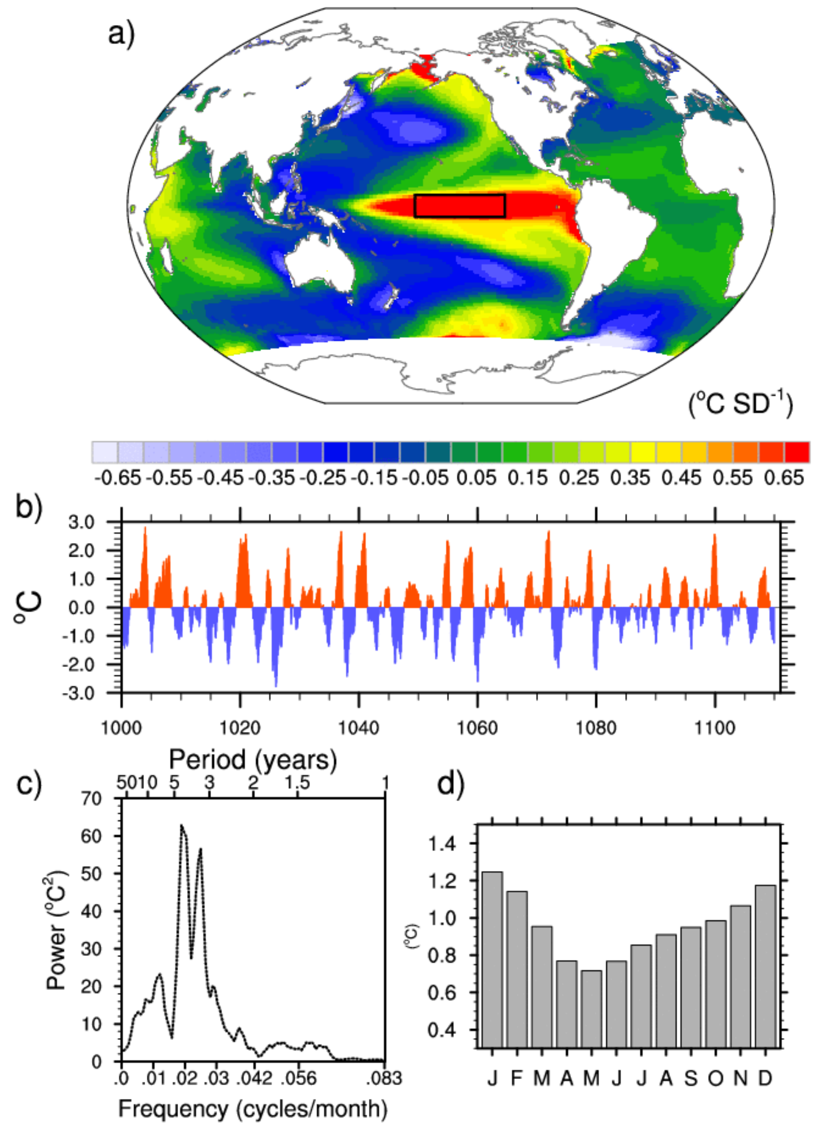


# Leading Mode of Global SST Variability
# Seasonal Capability (Neale, NCAR)

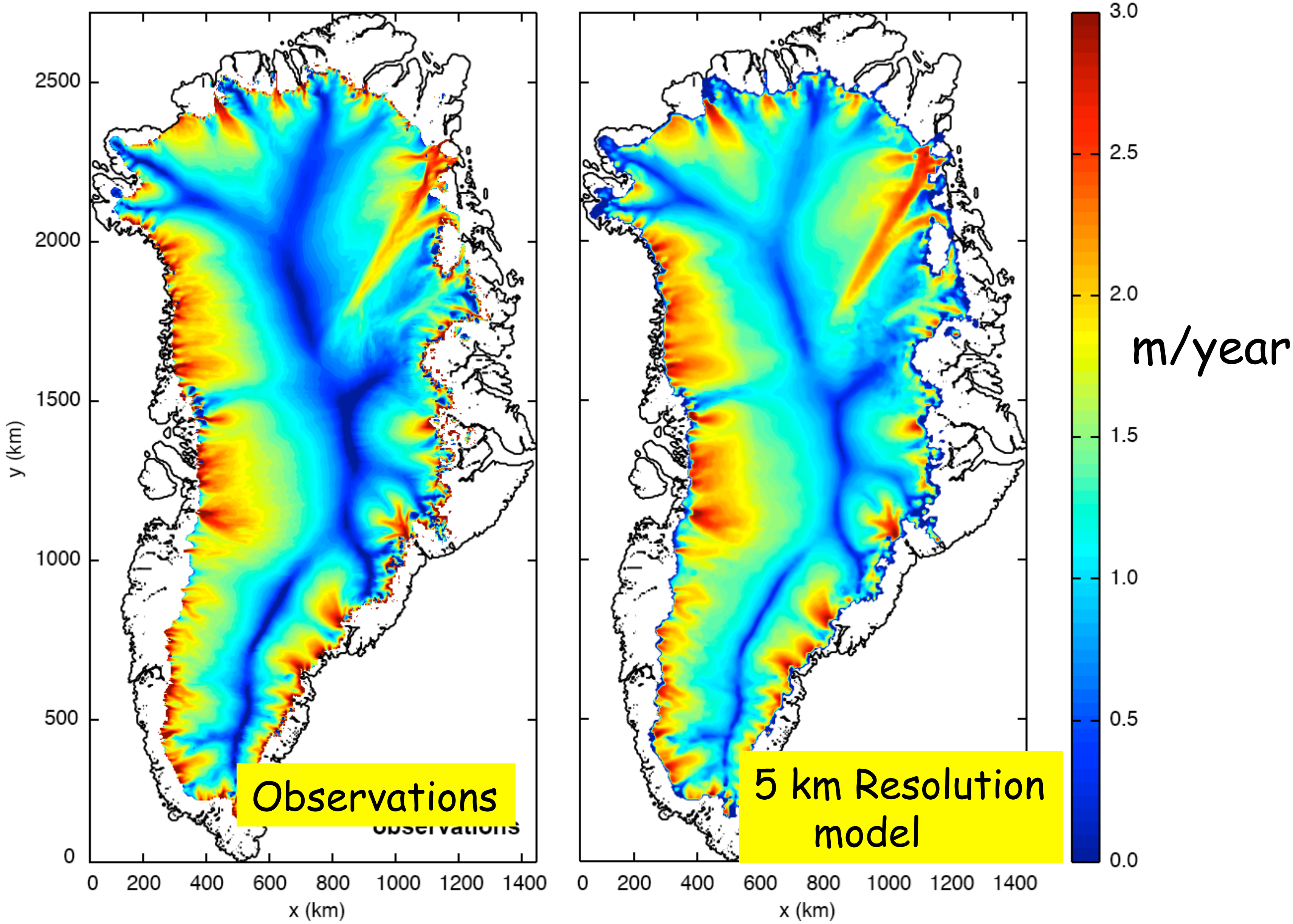
Observations




CCSM4



# Velocities

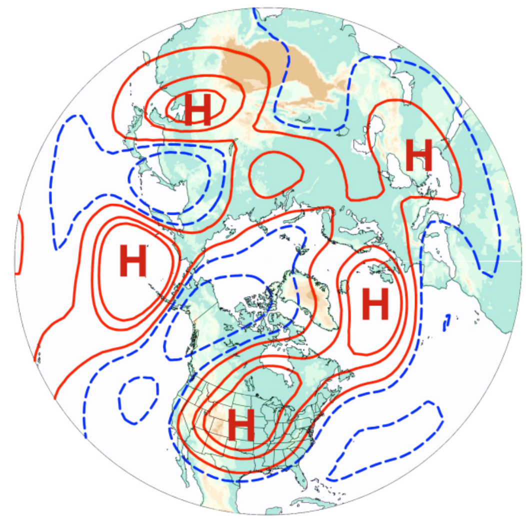



Price, Lipscomb et al, DOE/LANL, 2010

# Examples of NERSC Use

- 20th and 21st century simulations for IPCC
- Single forcing simulations
- Hurricane changes
- Closing Bering strait
- Heat waves, etc.
- Model development

# Probability of US heat Waves Affected by a Subseasonal Planetary Wave Pattern: Prediction 15-20 days in Advance


Haiyan Teng, Grant Branstator, Hailan Wang, Jerry Meehl, and Warren Washington, (2013) Nature Geoscience

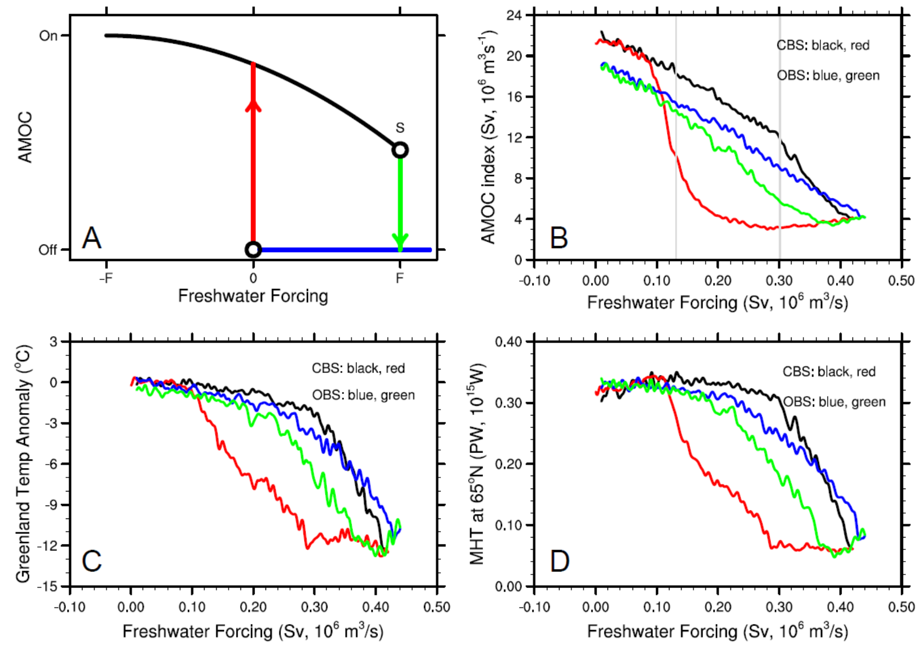
# Role of the Bering Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability

## Objective

Study the influence of the Bering Strait opening/closure on the hysteresis of the Atlantic meridional overturning circulation (AMOC) and abrupt climate change

## Approach

- *CCSM3* is used as the primary tool.
- Two simulations have done under present-day climate boundary conditions with everything is identical except one with an open Bering Strait and the other has a closed one.
- Freshwater is slowly added into the North Atlantic until the *AMOC* collapses, then freshwater water is slowly reduced until the *AMOC* restarts again. The simulations run 4400 years each at NERSC.

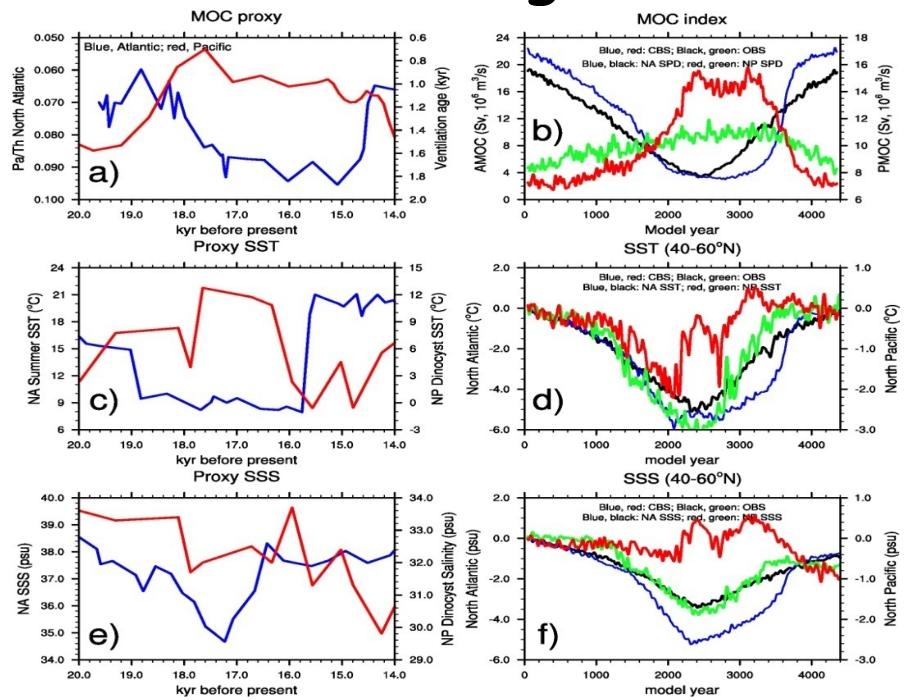



## Impact

- Our results suggest that *AMOC* hysteresis only exists when Bering Strait is closed. Thus abrupt climate changes occur only in glacial time.
- This could have broad impact on both past and future climate studies.

**Hu, A**, G. A. Meehl, W. Han, A. Timmermann, B. Otto-Bliesner, Z. Liu, W. M. Washington, W. Large, A. Abe-Ouchi, M. Kimoto, K. Lambeck and B. Wu, 2012, **Role of the Berig Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability**, *PNAS*, doi:10.1073/pnas.1116014109. (Highlighted by PNAS and receivedsignificant media attention)

# The Pacific-Atlantic Seesaw and the Bering Strait




## Objective

Study the influence of the Bering Strait opening/closure on the Pacific-Atlantic climate response to a collapse of the Atlantic meridional overturning circulation (AMOC)

## Approach

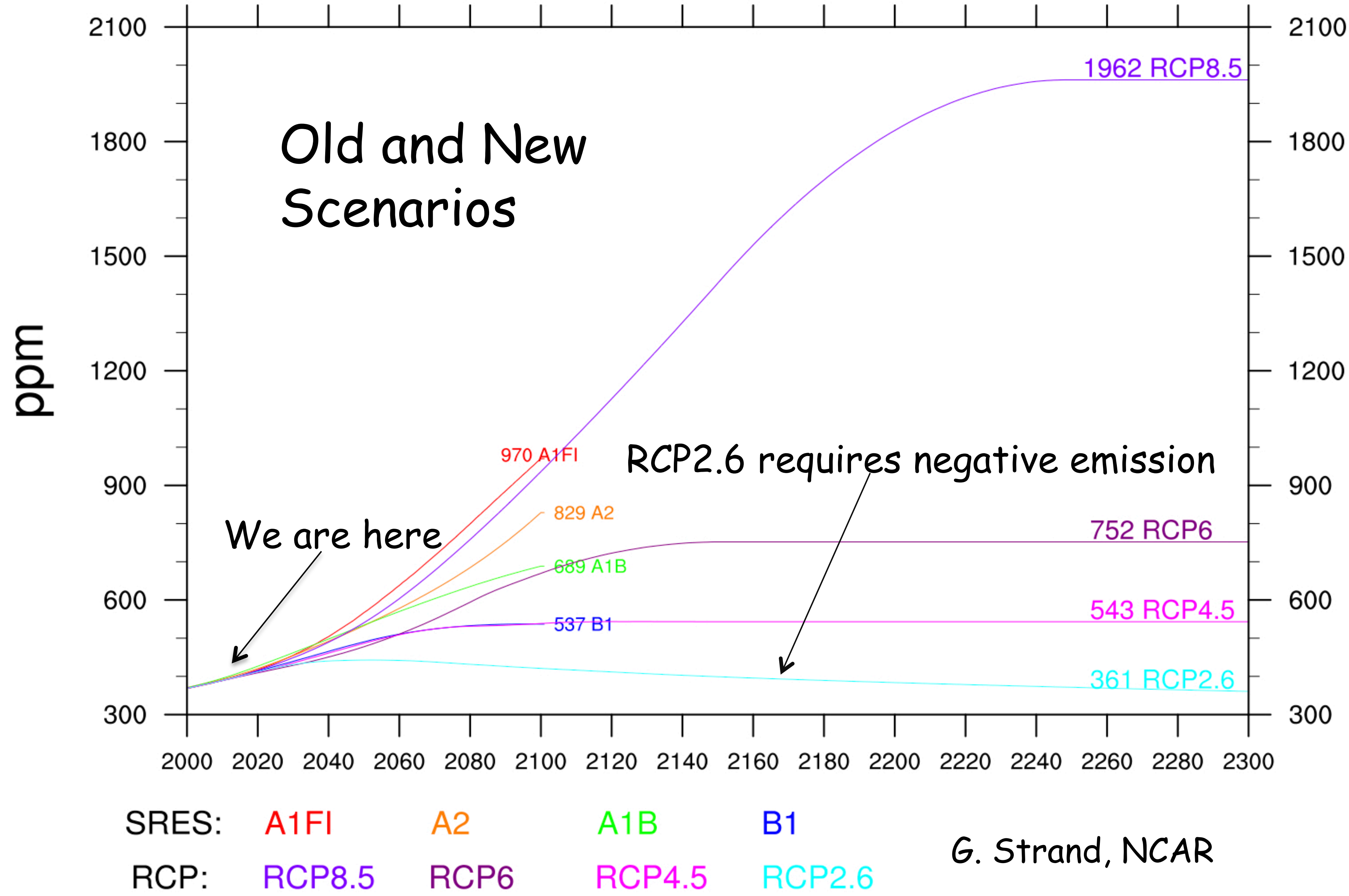
- CCSM3 is used as the primary tool.
- Two simulations have done under present-day climate boundary conditions with everything is identical except one with an open Bering Strait and the other has a closed one.
- Freshwater is slowly added into the North Atlantic until the AMOC collapses, then freshwater water is slowly reduced until the AMOC restarts again.

## Impact

- Our results suggest that a seesaw-like climate change due to an AMOC collapse can only occur with a closed Bering Strait.
- This could have broad impact on both past and future climate studies.

**Hu, A**, G. A. Meehl, W. Han, A. Abe-Ouchi, C. Morrill, Y. Okazaki, and M.O. Chikamoto, 2012, **The Pacific-Atlantic seesaw and the Bering Strait**, *Geophys. Res. Lett.*, L03702,doi:10.1029/2011GL050567. (Chosen to be AGU Research Spotlight)

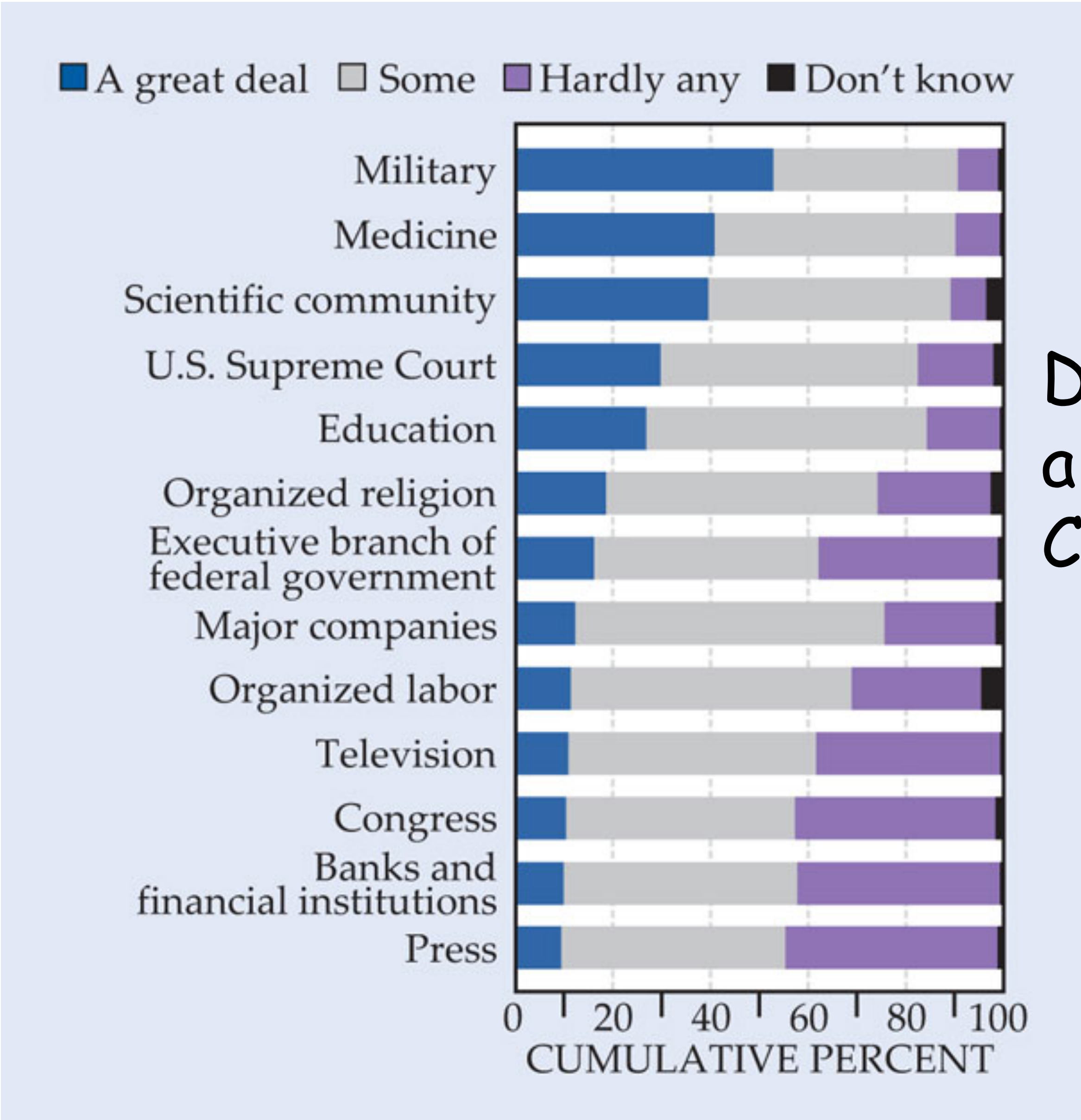
# $CO_2$ concentrations




G. Strand, NCAR


Climate and Earth System models have and continue to contribute to understanding and predicting the climate system. They allow the science community to determine objectively the possible impacts of climate change on food production, flooding, drought, sea level rise, and health as well as decision support. Higher resolution and more complete models will help.
From Istockphoto.com

# Professions: Public Trust




Debate in Congress about the President's Climate Action Plan

From National Science Board S & E Indicators (2012)

# Genesis of U.S. Global Change Program

White House Cabinet meeting on climate change in 1990

President George H. W. Bush

John Sununu, Chief of Staff

We installed a climate model in The White House!

Allan Bromley, President's Science Advisor

Convinced the cabinet about climate change.

We have loss the bipartisan approach.

# U.S. Global Change Research Program

$2.7 Billon over 12 agencies


**Thomas R. Armstrong, PhD**

Executive Director, USGCRP

Office of Science and Technology Policy

Executive Office of the President

Washington, DC


www.globalchange.gov

I chaired the Review Committee for the National Academies

Slides provided by Thomas Armstrong

# Global Change Research Act

**Global Change Research Act of 1190 (P.L. 101-606)**

**Act** at *http://www.globalchange.gov/about/program-structure/global-change-research-act*

Called for a "comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change"

**OMB/OSTP FY 14 S&T Memo:**
**Guidance to the Agencies**

**Memo** at *http://www.whitehouse.gov/sites/default/files/omb/memoranda/2012/m-12-15.pdf*

"Emphasize research that advances understanding of vulnerabilities in human and natural systems and their relationships to climate extremes, thresholds, and tipping points"

Passed by bipartisan Congress

# National Climate Assessment released on May 6, 2014 at the White House

# The End

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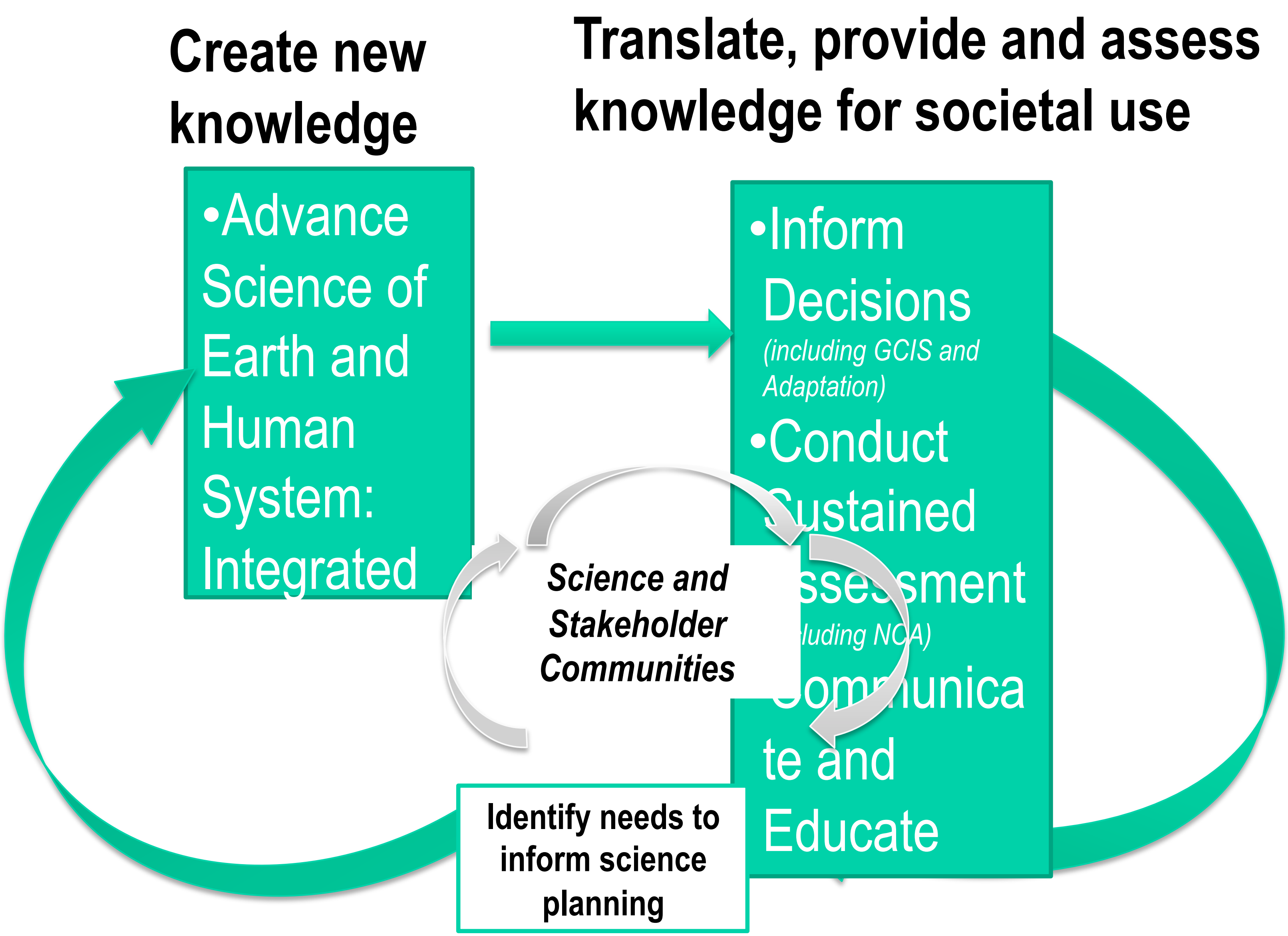
Special thanks to the
Department of Energy, Office of Science (BER),
the National Science Foundation (NSF), and OSTP

# USGCRP Research Enterprise



# USGCRP in the Federal Context

**Principals:** *http://globalchange.gov/about/program-structure/officials*


| CENRS Sub-Committees, WGs, & Task Forces |
|---|
| Air Quality Research (AQRS) |
| Critical and Strategic Mineral Supply Chains (CSMSC) |
| Interagency Arctic Research Policy Committee Interagency Working Group (IARPC) |
| Integration of Science and Technology for Sustainability Task Force |
| National Earth Observations Task Force (NEO) |
| Disaster Reduction (SDR) |
| Ecological Services (SES) |
| Global Change Research (SGCR) |
| Ocean Science & Technology (SOST) |
| Water Availability & Quality (SWAQ) |
| Toxics & Risks (T&R) |
| US Group on Earth Observations (USGEO) |

# Research Goals
# U.S. Global Change Research Program

- Goal 1. Advance science: Earth system understanding, science of adaptation and mitigation, observations, modeling, sharing information
- Goal 2. Inform decisions: Scientific basis to inform, adaptation and mitigation decisions
- Goal 3. Conduct sustained assessments: build capacity that improves Nation's ability to understand, anticipate, and respond
- Goal 4. Communicate and educate: Advance communication and educate the public, improve the understanding of global change, develop future scientific workforce

# The USGCRP Strategic Plan
## Outcomes and Priorities Activities

### Outcomes
- Providing Knowledge on Scales Appropriate for Decision Making
- Incorporating Social and Biological Sciences
- Enabling Responses to Global Change via Iterative Risk Management

### Priorities Activities
- Enhance Information Management and Sharing
- Enable new capabilities for Integrated Observations and Modeling
- Increase Proactive Engagement and Partnerships
- Leverage International Investments & Leadership
- Develop the Scientific Workforce for the Future