Computer Modeling of the 20th and 21st Century Climate Change

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National Center for Atmospheric Research

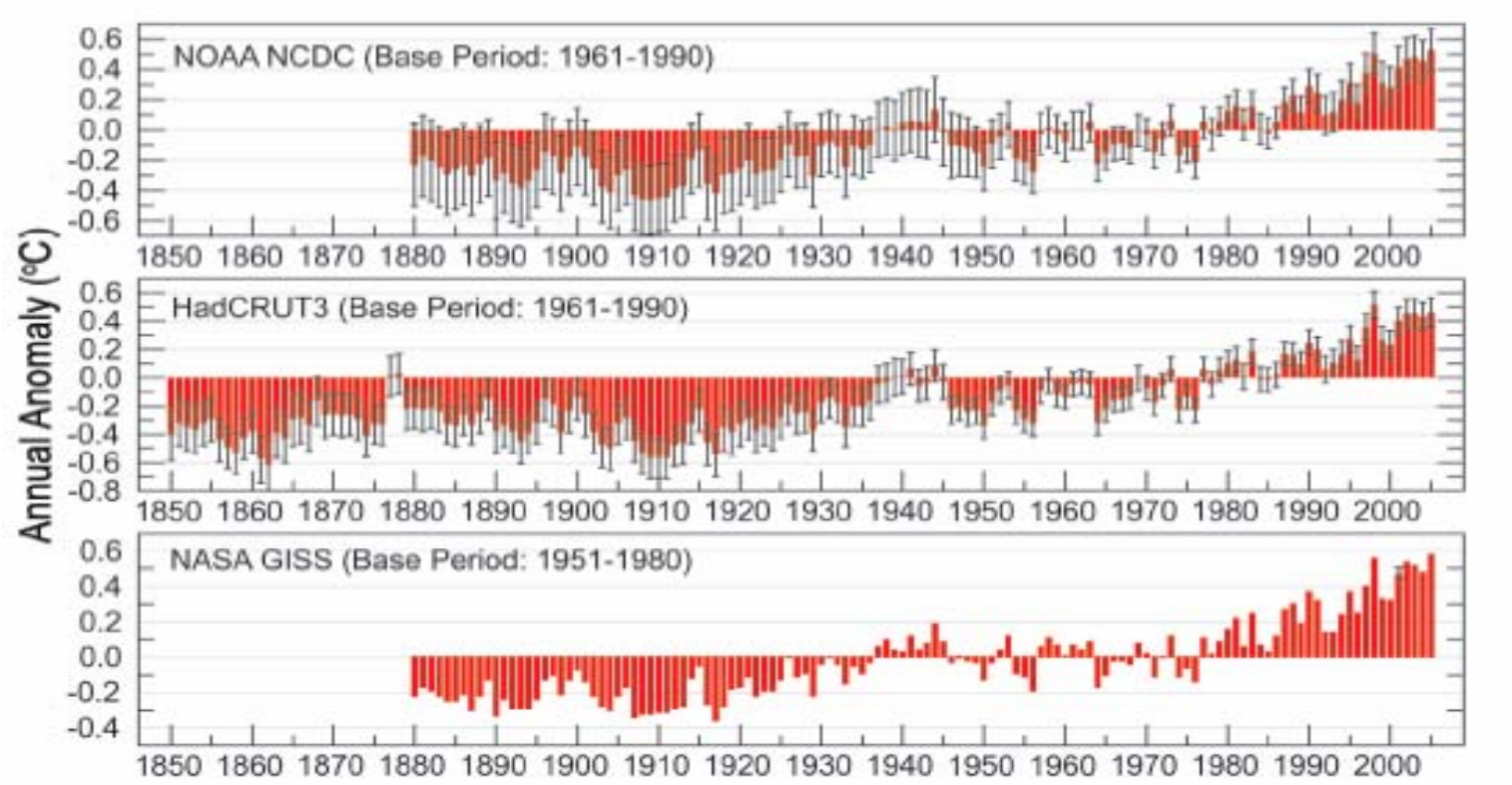
EPSCOR NREL Talk
July 24, 2007

NCAR

Overview

- A few examples of climate change
- What is in a climate model?
- How can we stabilize global warming?
- Mitigation versus adaptation
- Can we limit global warming to 2°C from years 1870 to 2100?
- What does this mean in terms of cutting fossil fuel and other emissions?

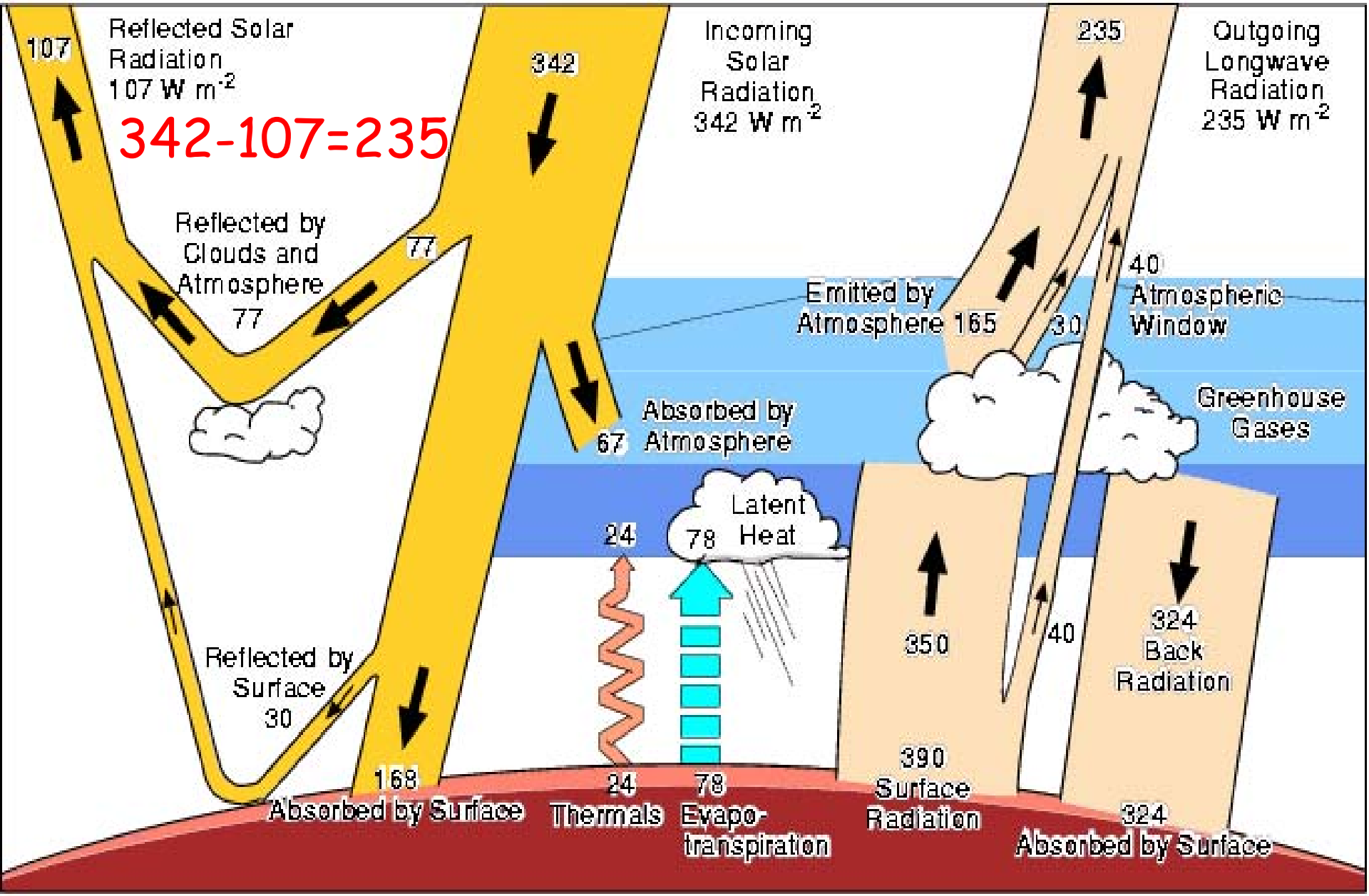
Global Temperature Trends



January 2007 warmest on record…D. Easterling, NOAA, Summer of 2007 ???

National Geographic Magazine – July 2007

Global Heat Flows



Kiehl and Trenberth, 1997

What is the status of state-of-the-art climate models and their transition to earth system models?

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

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

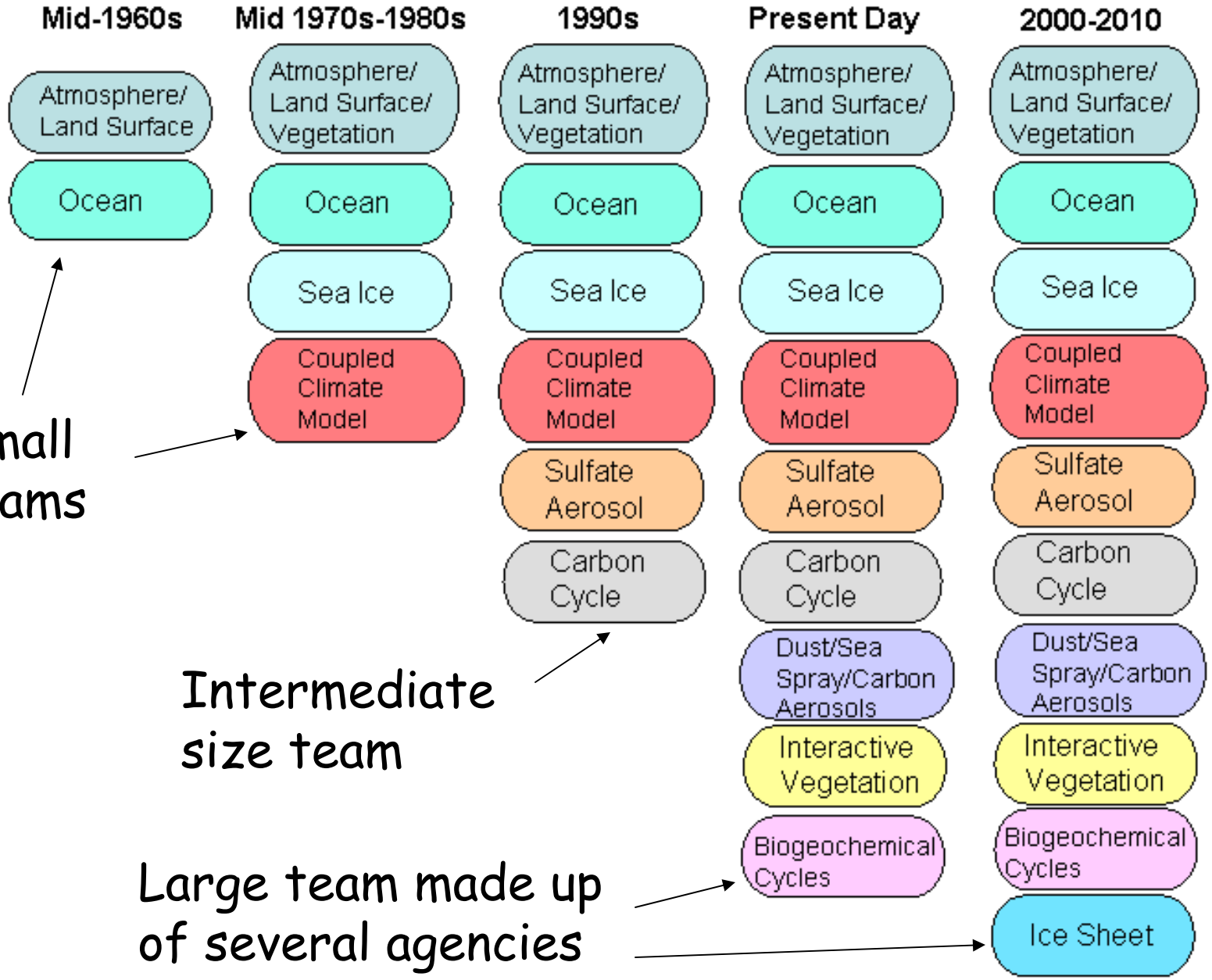
$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

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

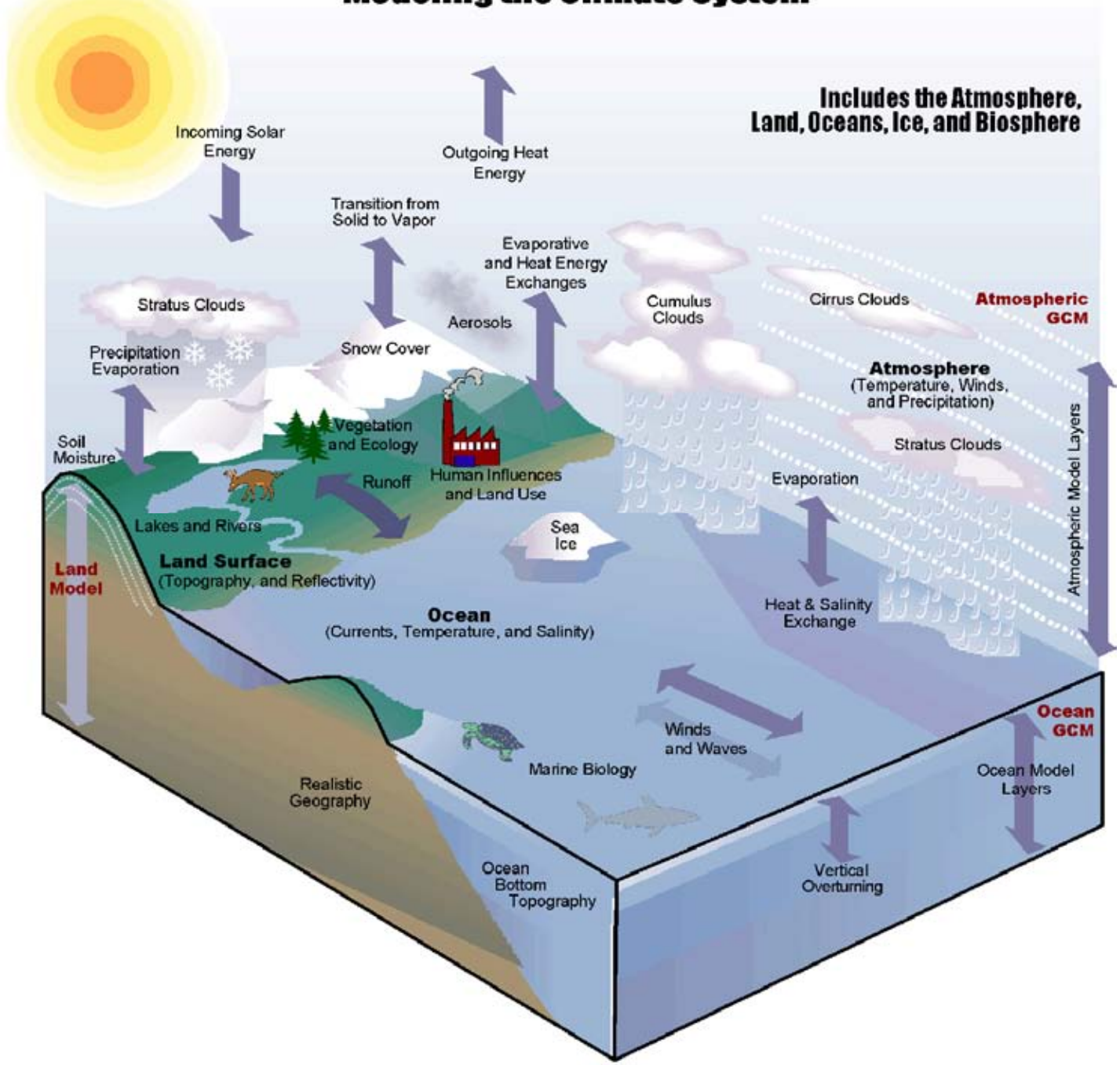
$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

Equations known in 1904!

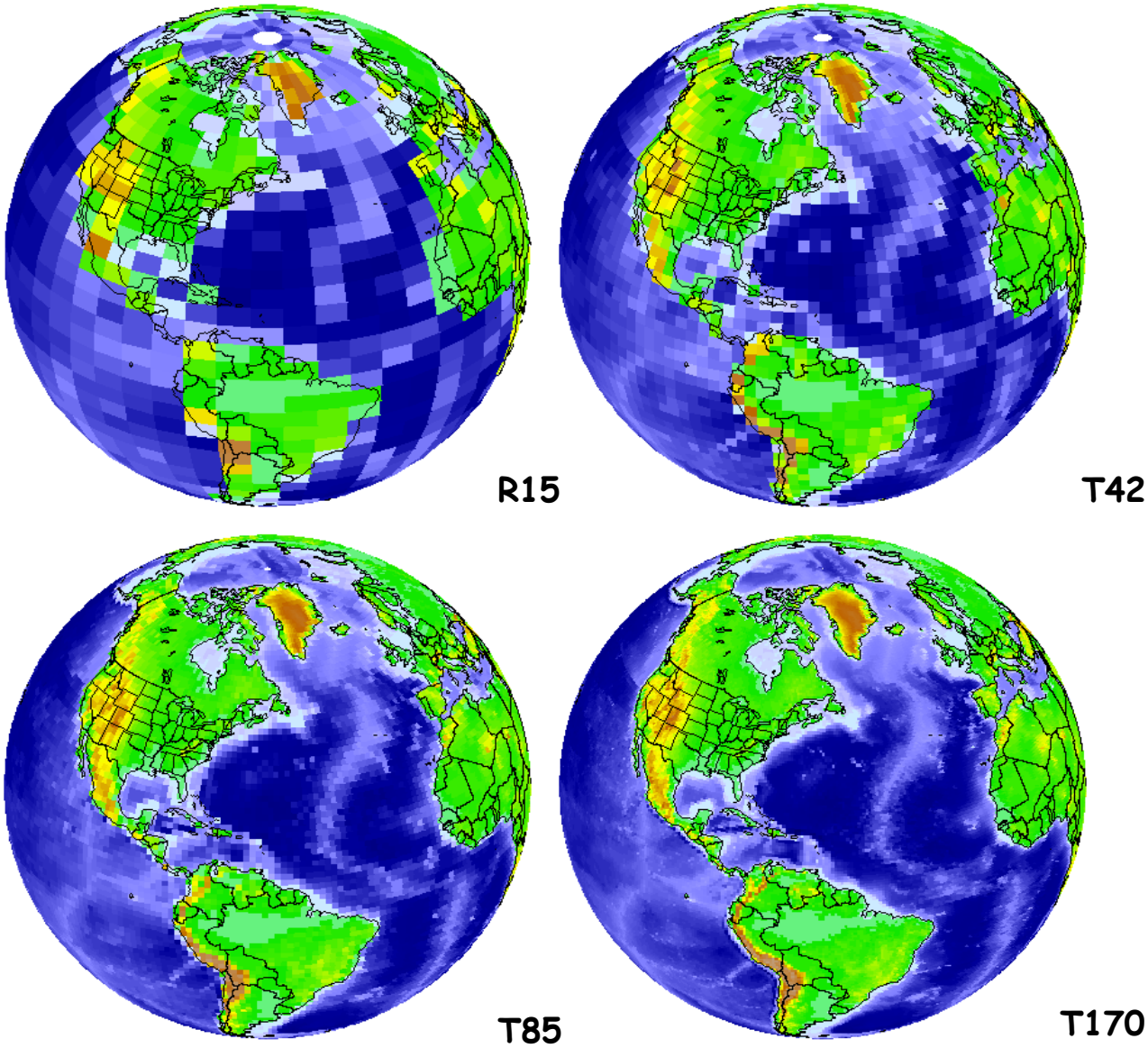
Timeline of Climate Model Development

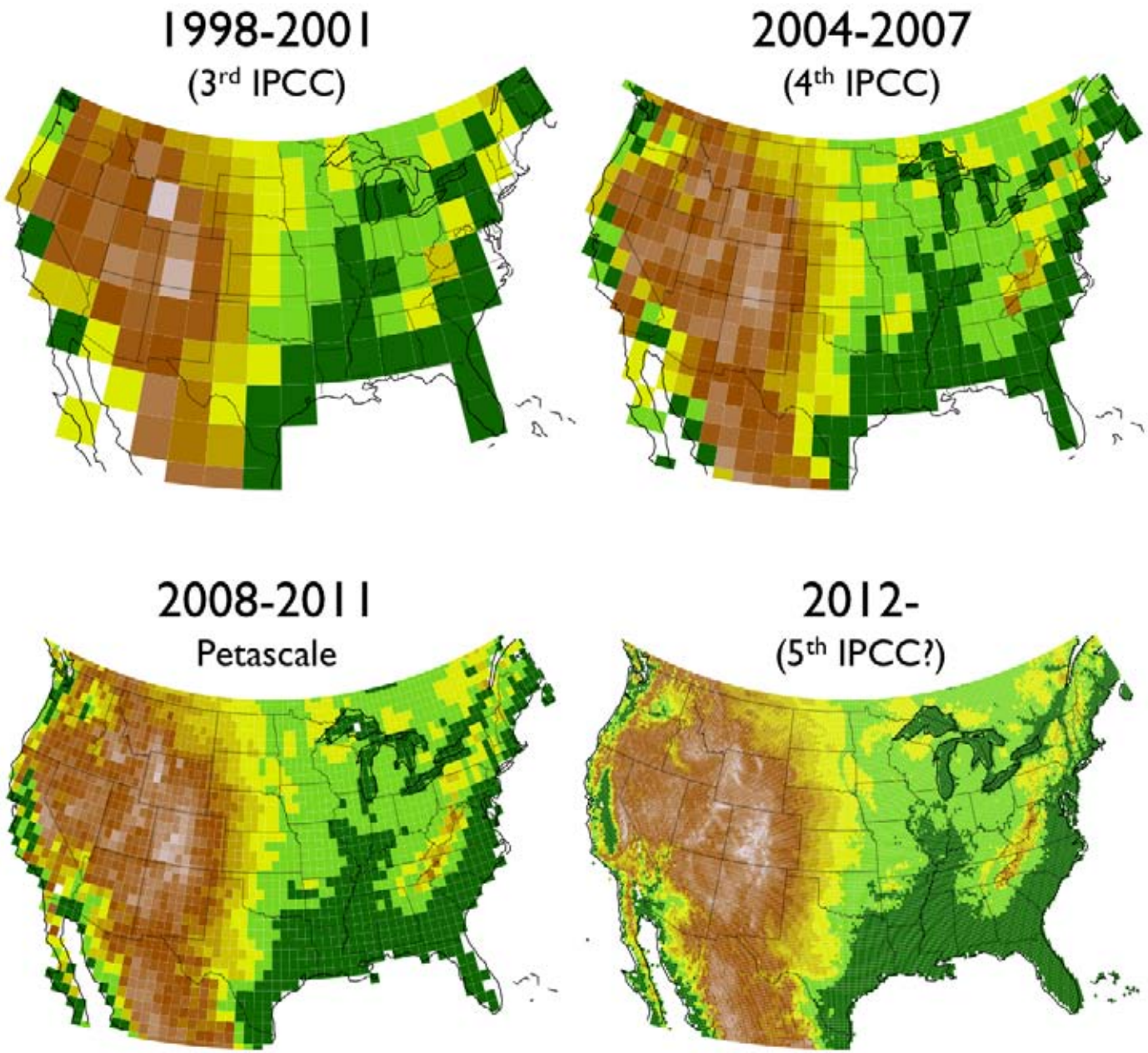


Modeling the Climate System

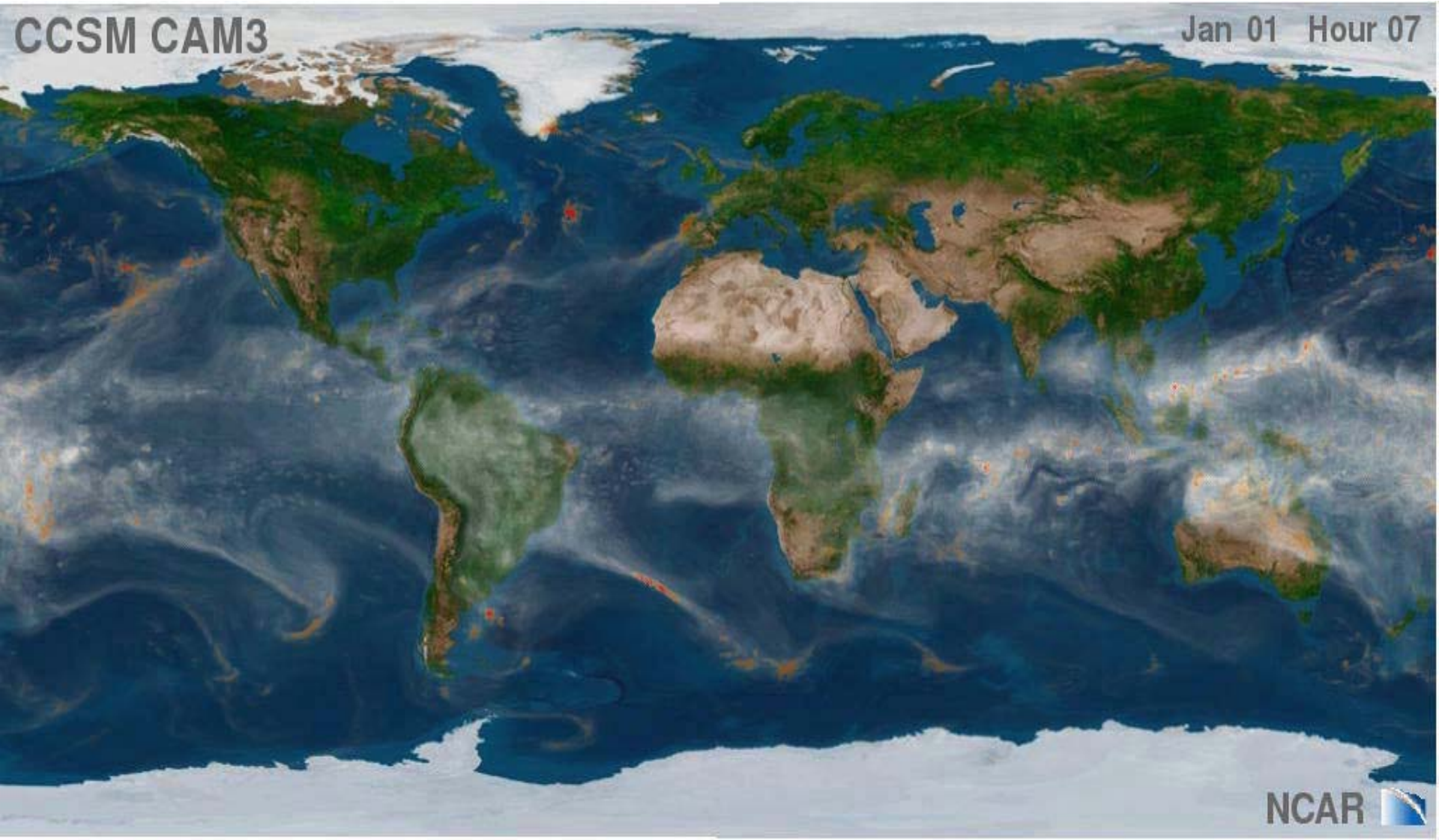


Model Resolutions

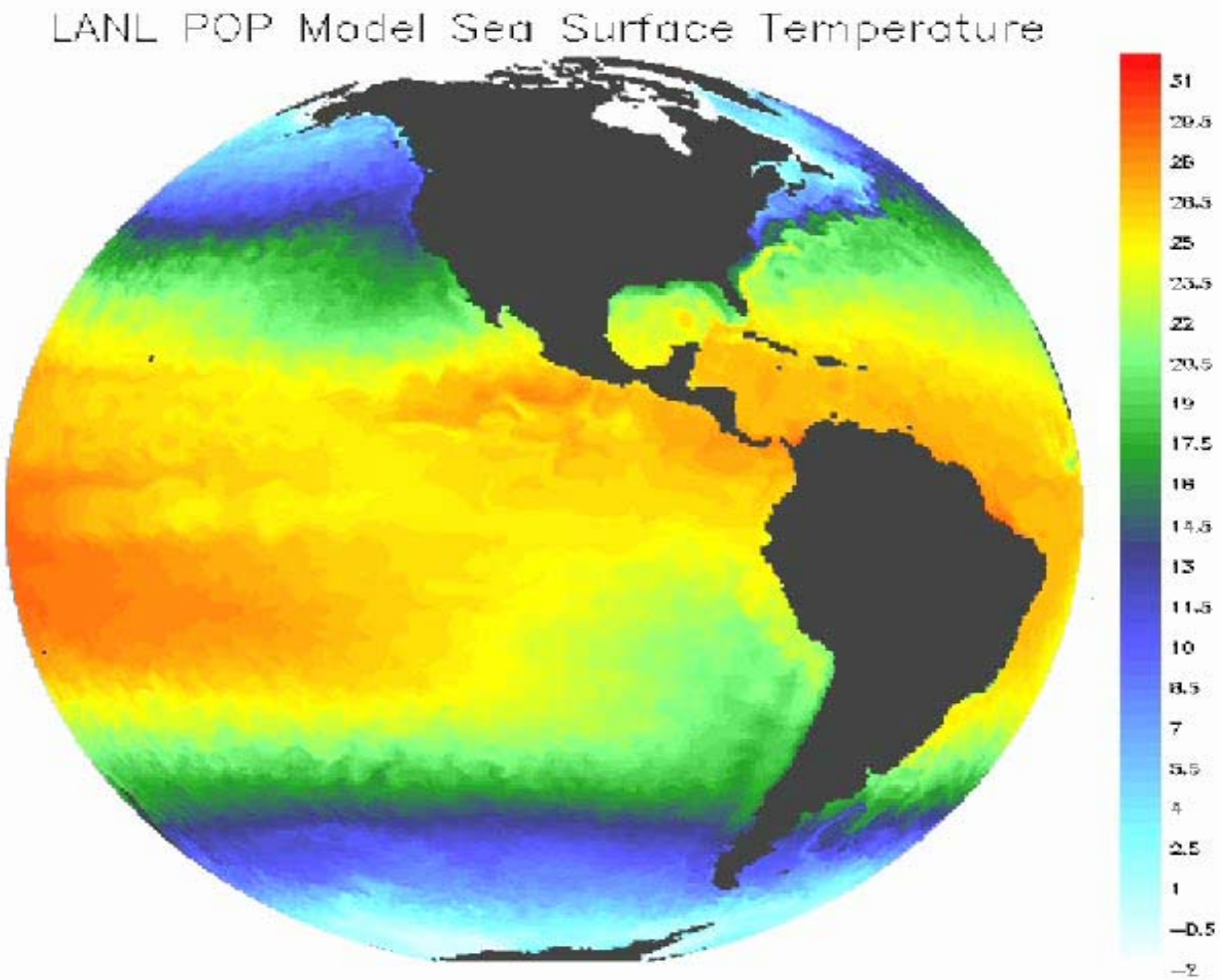



1998-2001
(3rd IPCC)
2004-2007
(4th IPCC)
2008-2011
Petascale
2012-
(5th IPCC?)

Water Vapor transport and Precipitation (orange) T341-approx 37 Km (J. Hack)



High Resolution Ocean (LANL) (0.10°)



Mt Pinatubo eruption in the Philippines, June 15, 1991. Gases and solids injected 20 km into the stratosphere.

From Church, White, & Arblaster

Source: World Resources 2000-2001 Time Magazine – 9 April 2001

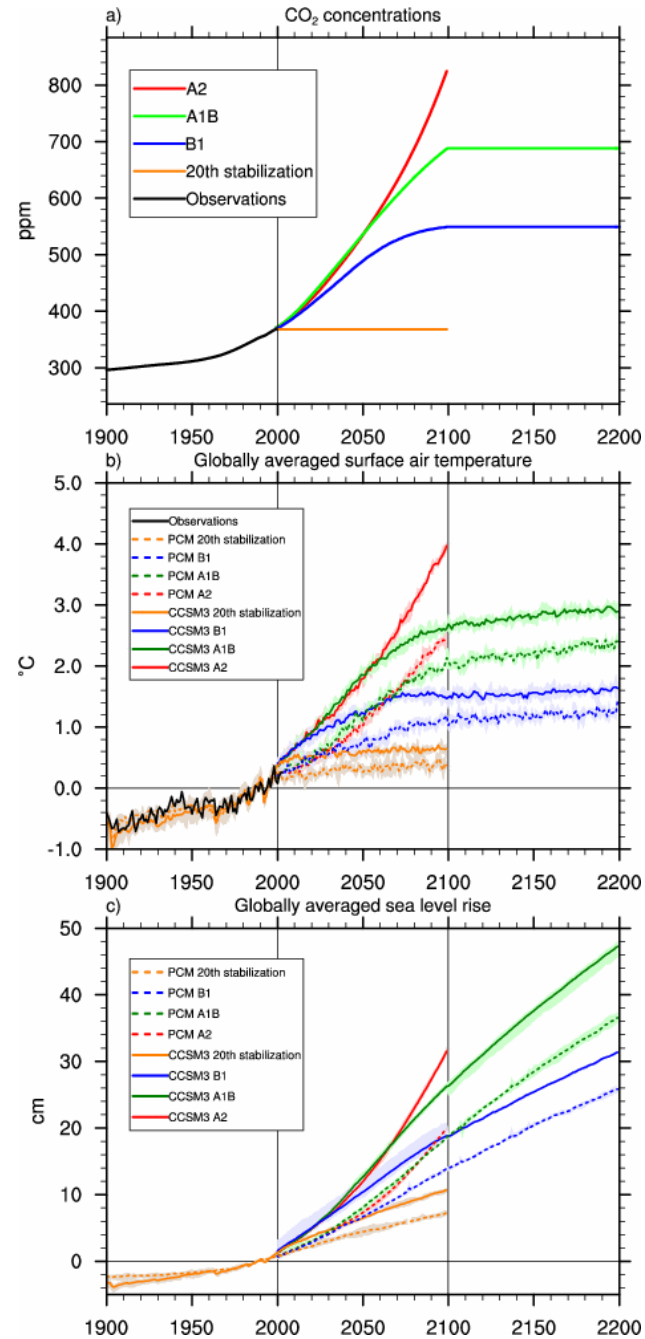
Note China will exceed U. S. emissions in 2009;
they are building a coal power plant every week!

Climate Change Scenarios:

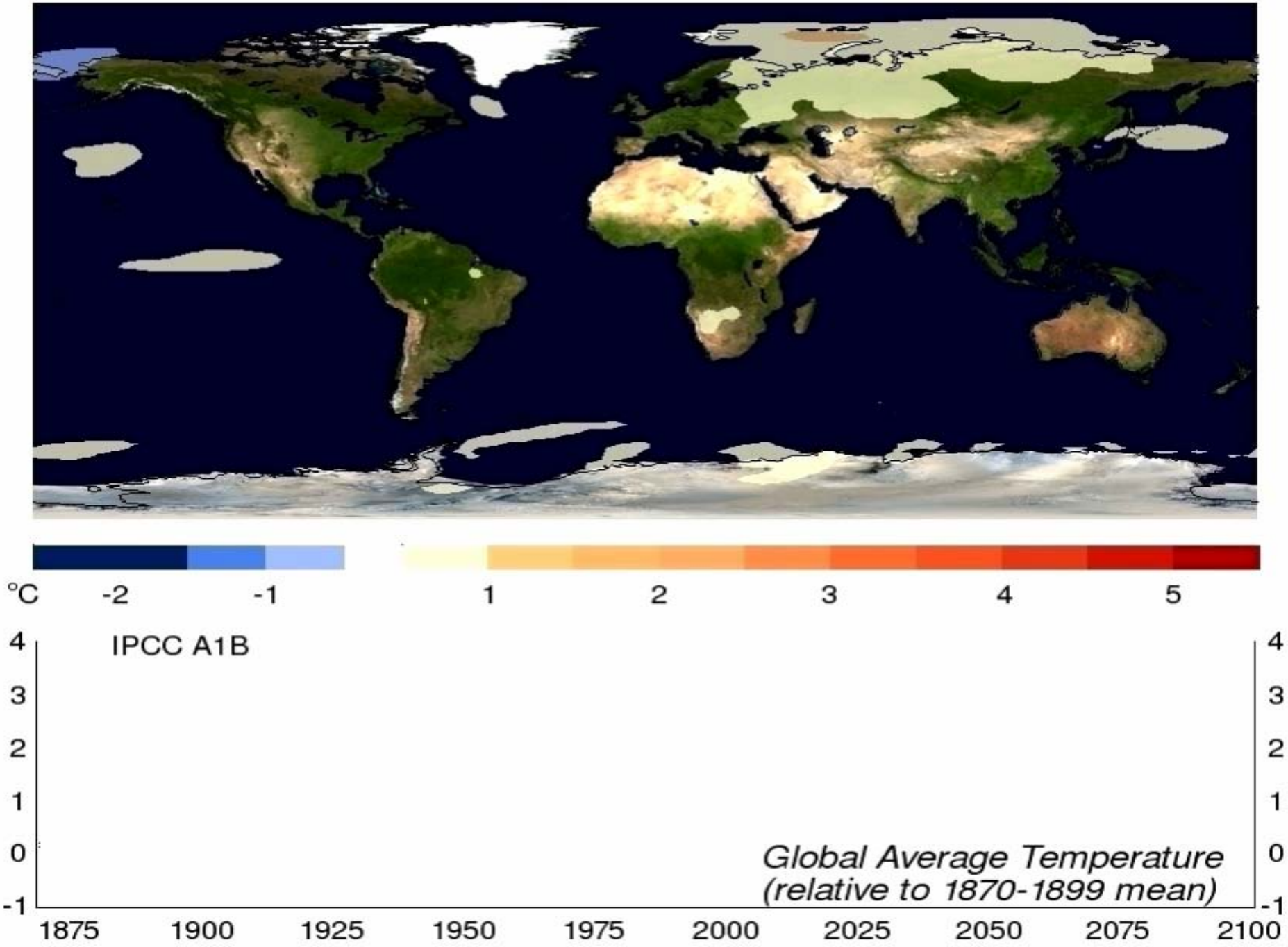
At any point in time, we are committed to additional warming and sea level rise from the radiative forcing already in the system.

Warming stabilizes after several decades, but sea level from thermal expansion continues to rise for centuries.

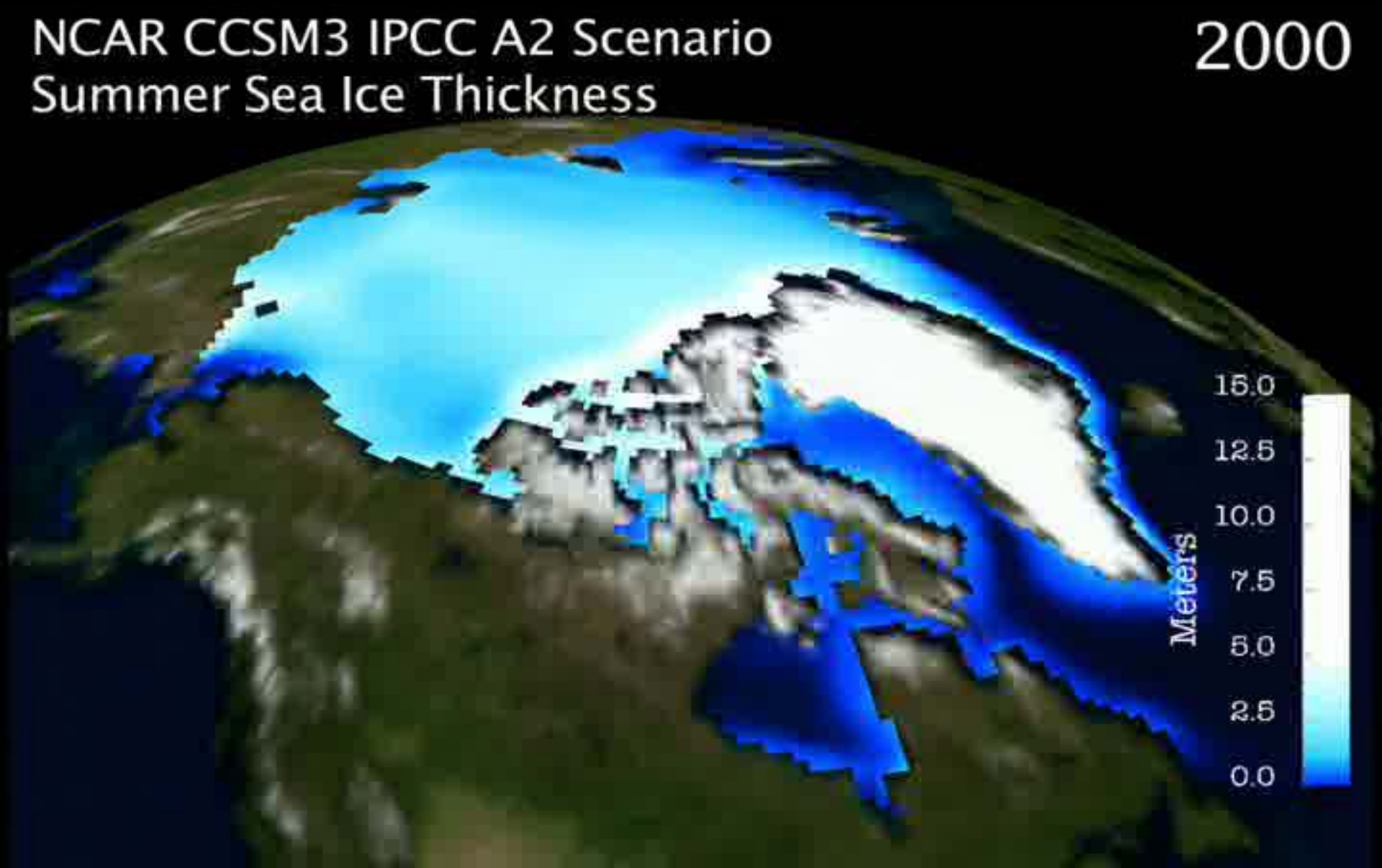
Each emission scenario has a warming impact.



(Meehl et al., 2005: How much more warming and sea level rise? *Science*, **307**, 1769-1772)


°C
-2
-1
1
2
3
4
5
IPCC A1B
Global Average Temperature
(relative to 1870-1899 mean)
4
3
2
1
0
-1
1875
1900
1925
1950
1975
2000
2025
2050
2075
2100

Under the Scenario A2…Business-As-Usual: This is What Happens to Arctic Sea Ice (Holland, NCAR)



Heat Waves

Impacts on human health and mortality, economic impacts, ecosystem and wildlife impacts

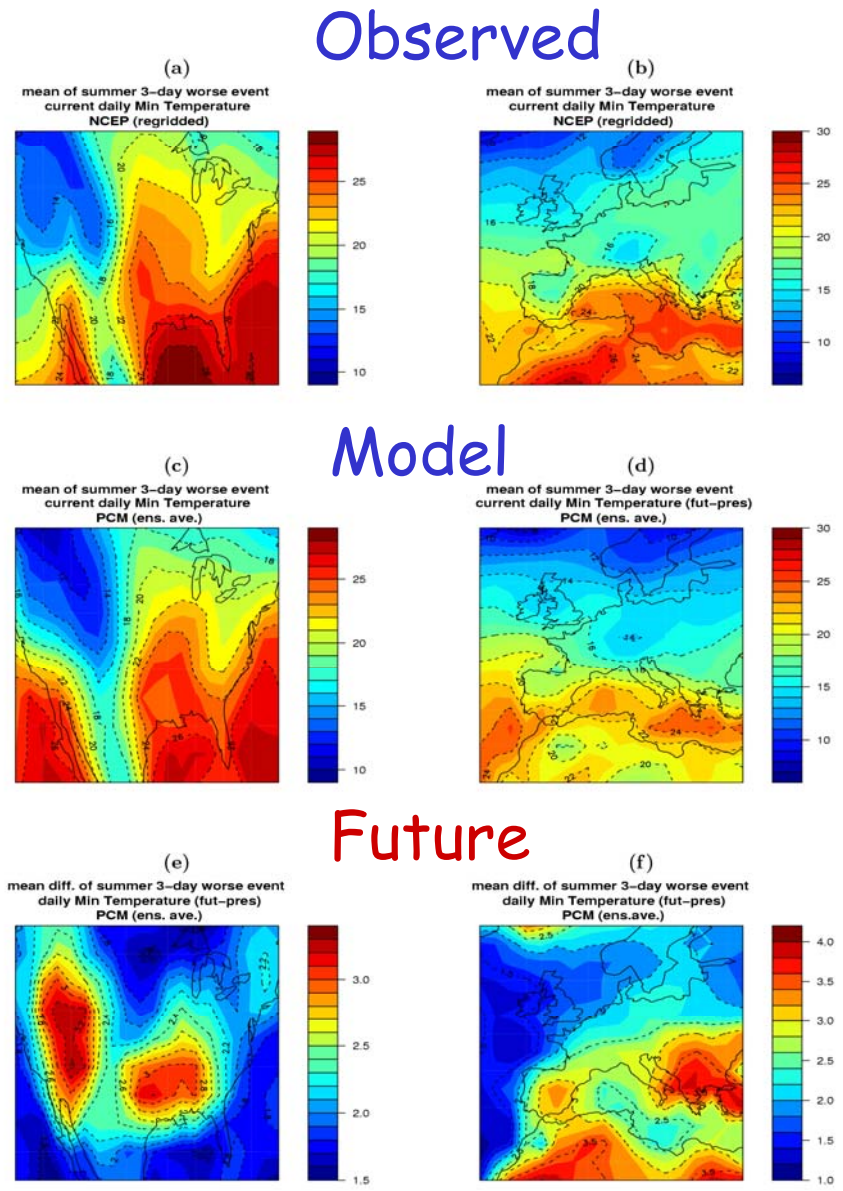
(Meehl and Tebaldi, 2004: More intense, more frequent and longer lasting heat waves in the 21st century, *Science*, 305, 994-997)

Climate models can be used to provide information on changes in extreme events such as heat waves

Heat wave severity defined as the mean annual 3-day warmest nighttime minima event

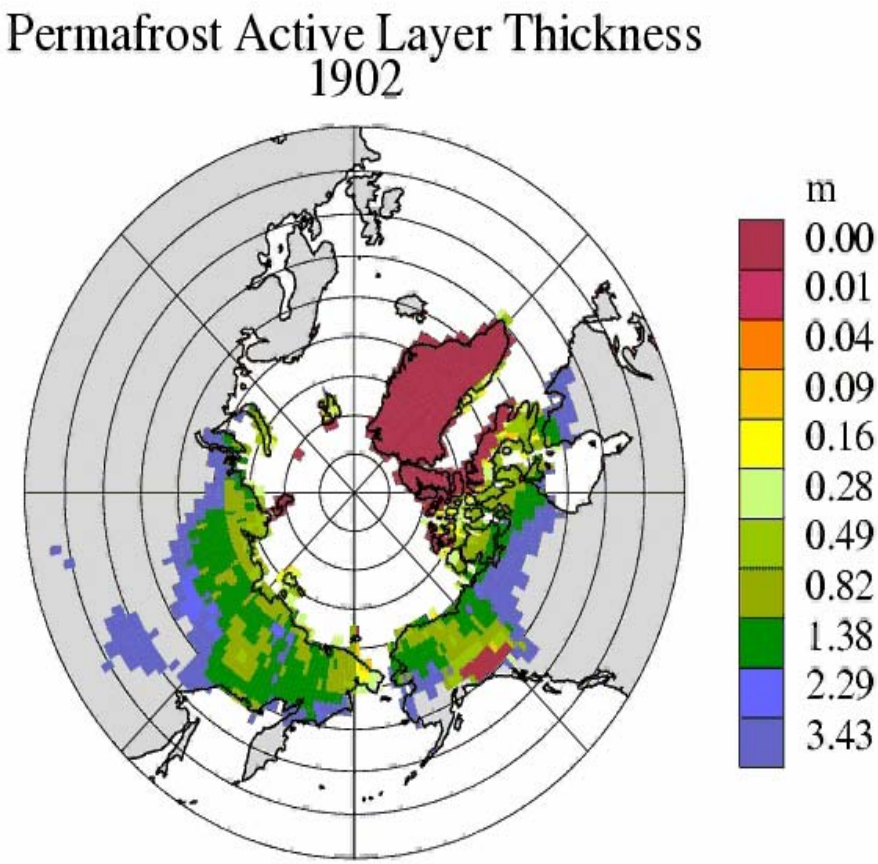
Model compares favorably with present-day heat wave severity

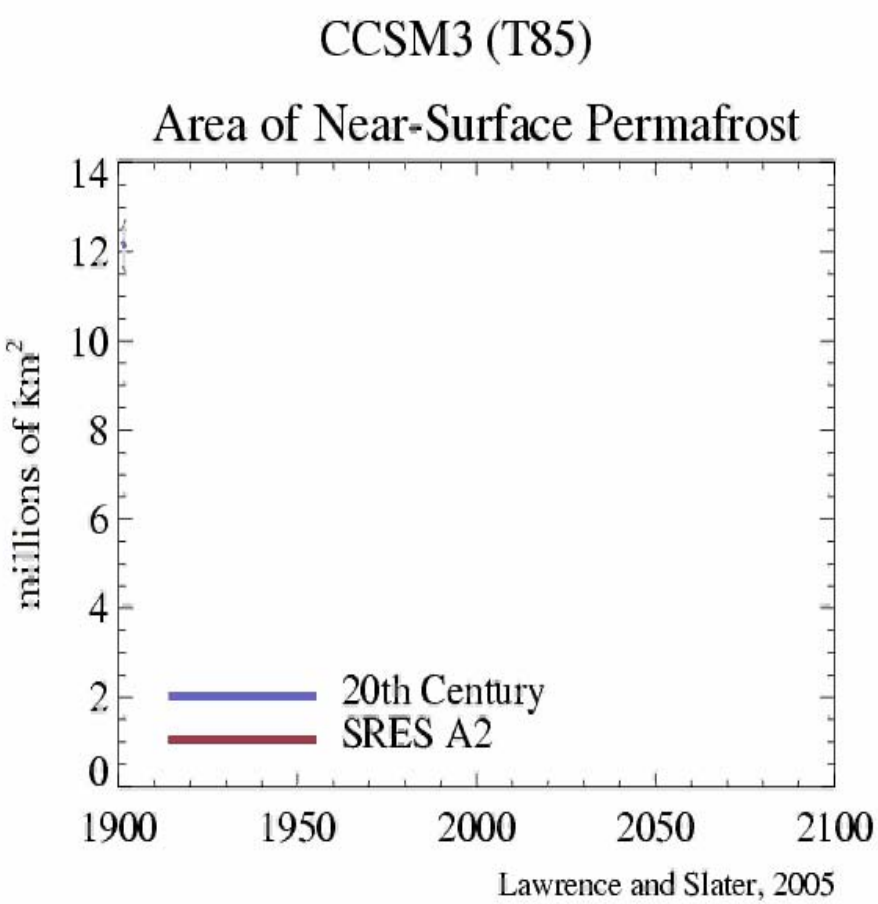
In a future warmer climate, heat waves become more severe in southern and western North America, and in the western European and Mediterranean region



From Meehl and Tebaldi 2005

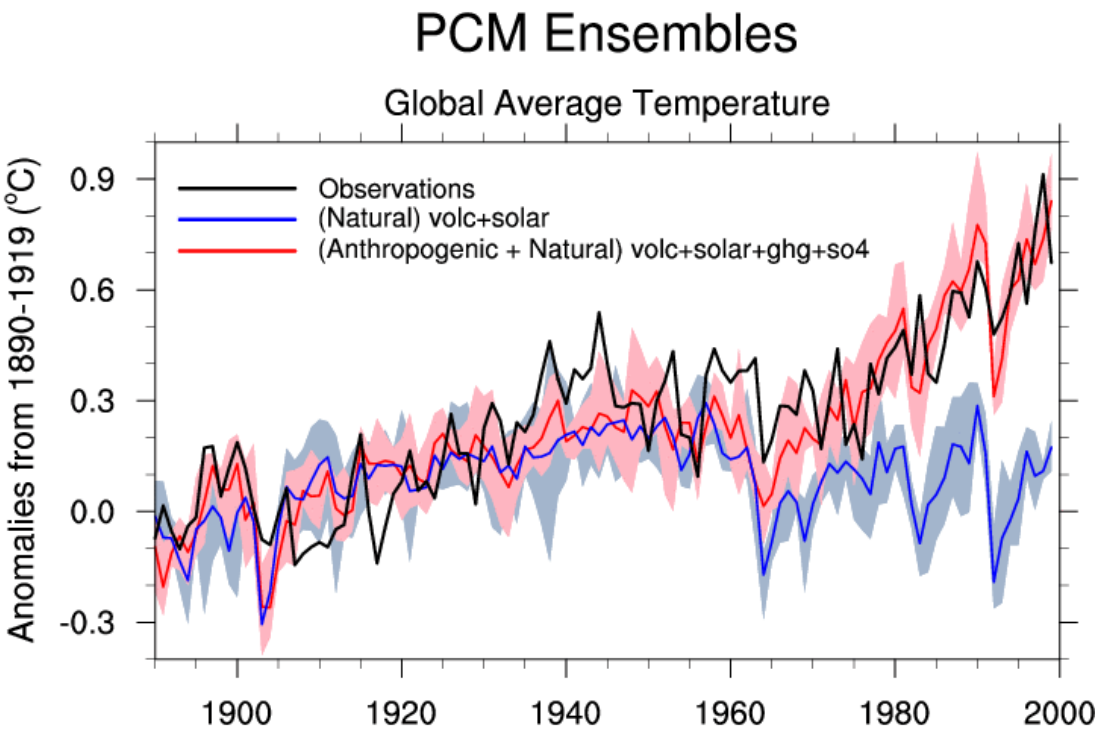
Historical and Future Changes in Permafrost
(D. Lawrence, NCAR)





Natural Variations Do Not Explain Observed Climatic Change

- Climate models with natural forcing (including volcanic and solar) do not reproduce warming
- When increase in greenhouse gases is included, models do reproduce warming
- Addition of increase in aerosols (cooling) improves agreement

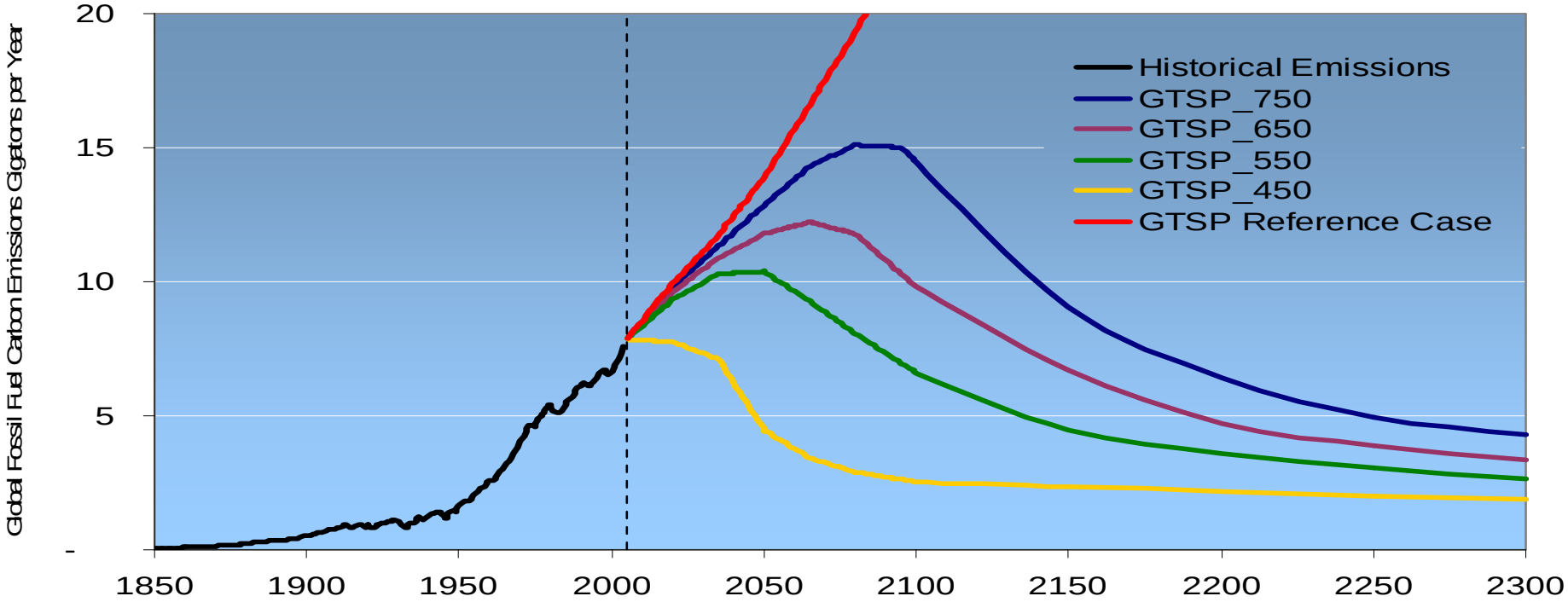


Assumptions

- Scenarios used in IPCC all assume non-fossil fuel emission strategies that will not slow down until after 2030.
- IPCC scenarios would lead to CO_2 concentrations to exceed 450 ppm.
- If conservation, renewables, solar, wind, biomass, and nuclear became a larger component of energy mix, it is possible that CO_2 concentration could be limited to roughly 450 ppm and we could limit warming from 1870 to 2100 to 2°C.

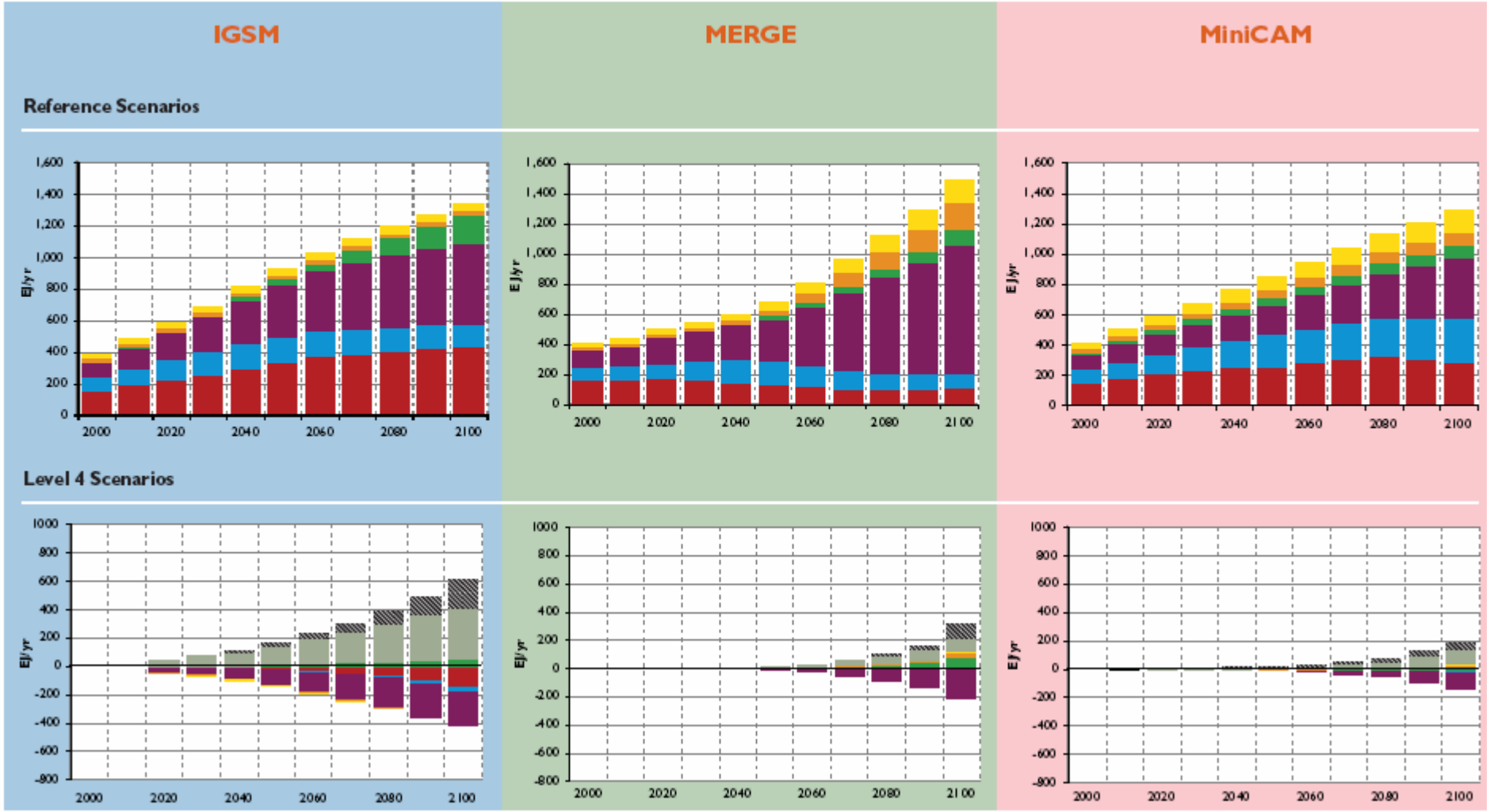
Climate Change is a Long-term Strategic Problem…notice tails on graph

PNNL Global Energy Technology Strategy Project (GTSP) Estimates

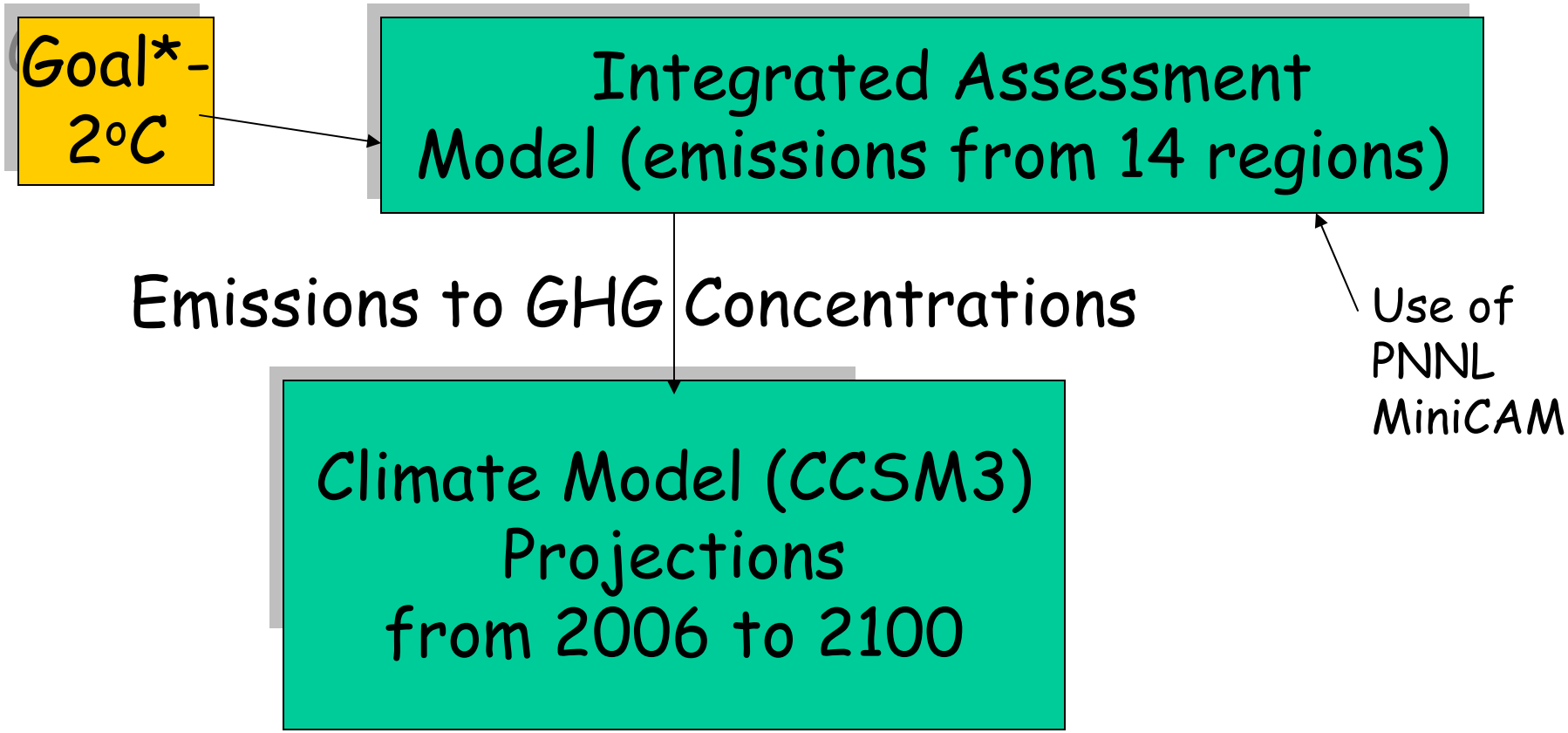


- Stabilization of greenhouse gas **concentrations** is the goal of the Framework Convention on Climate Change.
- Stabilizing CO_2 **concentrations** at any level means that **global**, CO_2 emissions must peak and then decline forever.
- Report released in July 2007 by energy experts that emissions will increase by 50% over next 30 years or so.

CCSP Integrated Assessment Models

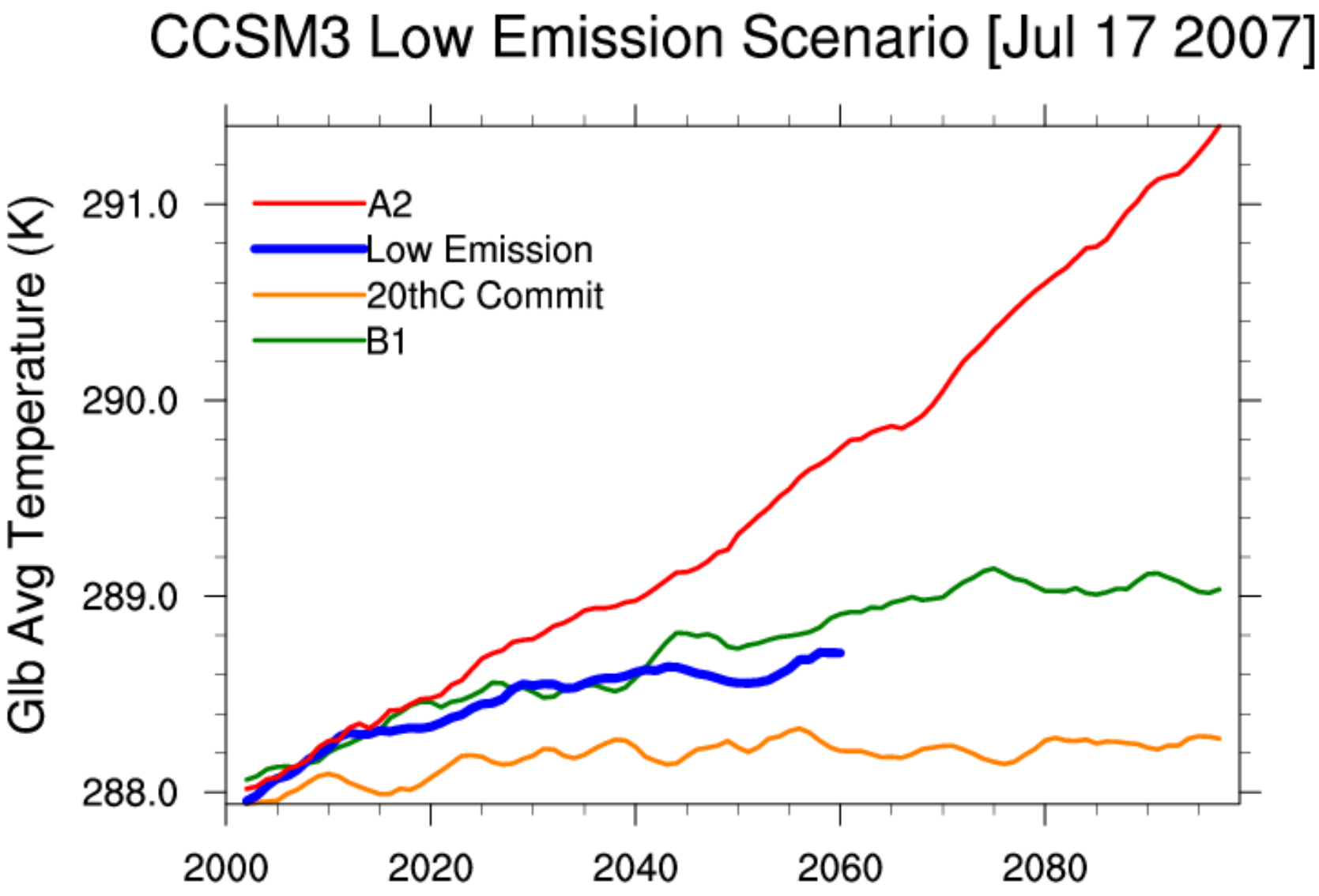


Steps to Low Emission Climate Change Projections



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

Jae Edmonds and Steve Smith solution.

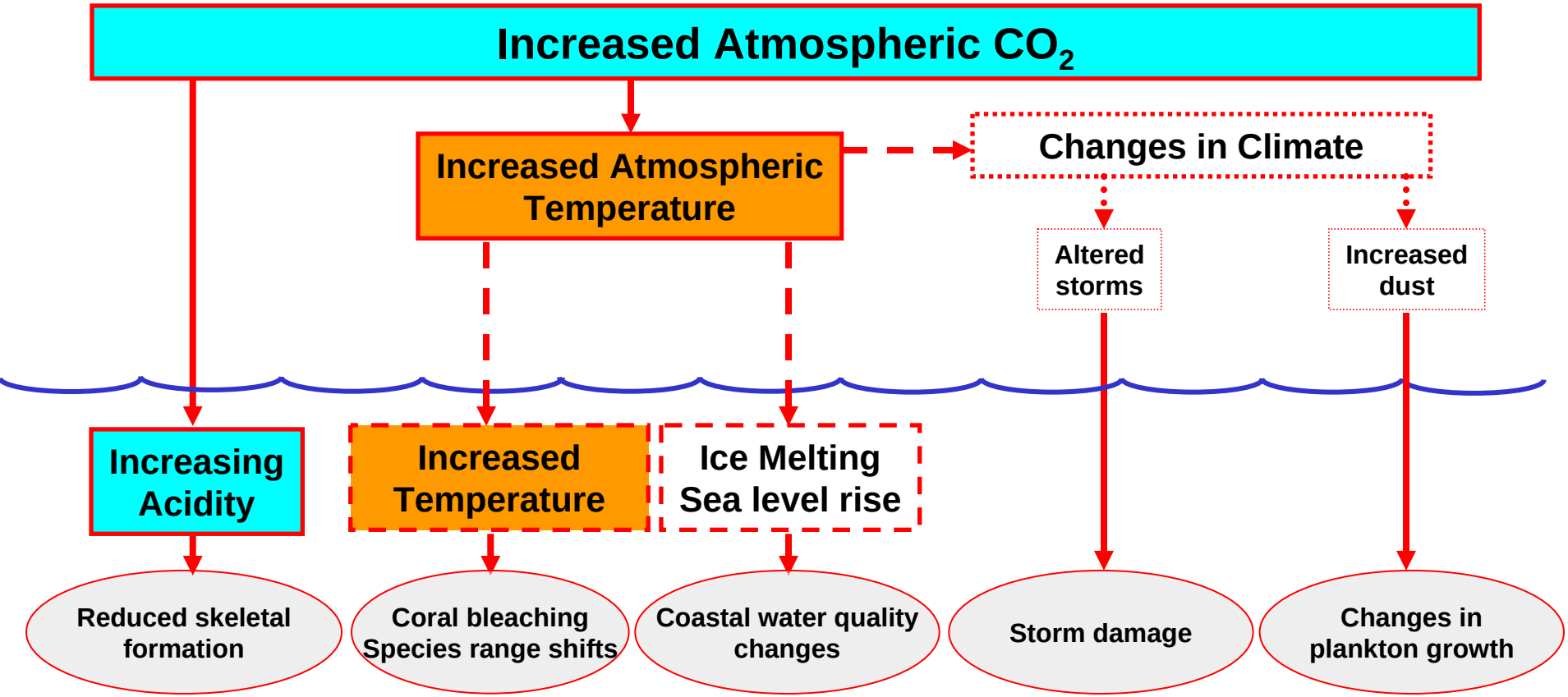

CCSM3 Low Emission Scenario [Jul 17 2007]
Glb Avg Temperature (K)
291.0
290.0
289.0
288.0
2000
2020
2040
2060
2080
A2
Low Emission
20thC Commit
B1

Collaboration with:

- National Renewable Energy Laboratory (NREL)
- Pacific Northwest Laboratory
- Lawrence Livermore National Laboratory
- National Center for Atmospheric Research

MELTING
DOES WELL AT THE POLES.
THE NEW H2.
HUMMER
LIKE NOTHING ELSE.
VIACOM
NOTE

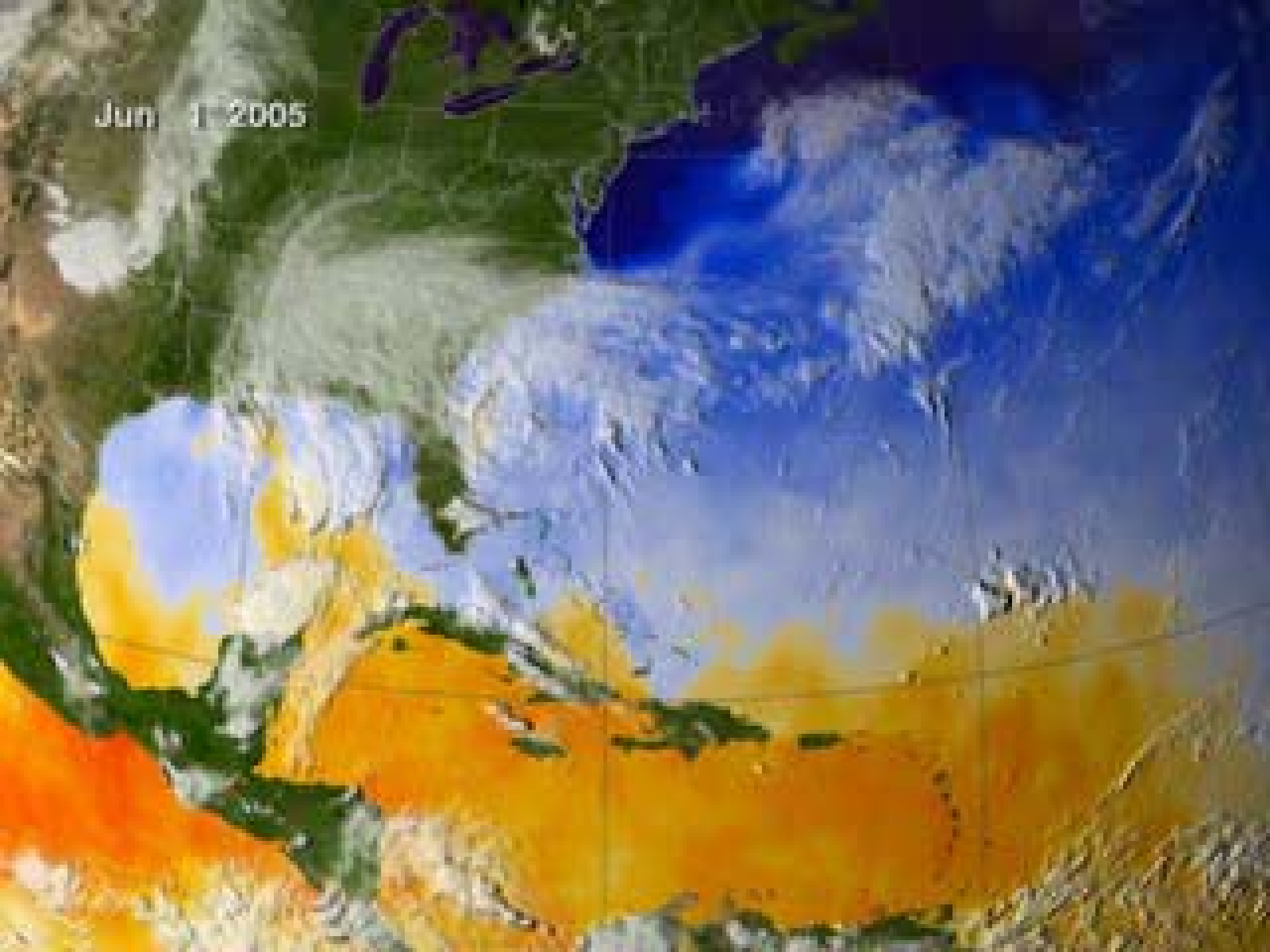
Effects of Increasing Atmospheric CO_2 on Marine Ecosystems



Changes in Atlantic Hurricanes

The increasing sea surface temperatures will increase the number of category 4 and 5 hurricanes says the study by Hoyos, Agudelo, Webster, and Curry, SCIENCE 2006.

This conclusion still not accepted by some of the research community!


Jun 1 2005

AARP Magazine July 2007……
it takes all types to solve this problem

1. Senator John McCain (R-AZ) **2.** Ellen Mosley-Thompson, of Ohio State University (OSU), has studied climate change for over 30 years **3.** Bonnie Raitt **4.** Pat Robertson **5.** Warren Washington, head of climate-change research at the National Center for Atmospheric Research **6.** Governor Arnold Schwarzenegger (R-CA) **7.** Martin I. Hoffert, an NYU professor and energy-research proponent **8.** Senator Barbara Boxer (D-CA) **9.** Senator Joe Lieberman (ID-CT) **10.** One-time skeptic Rupert Murdoch **11.** Tony Blair **12.** Sheila Watt-Cloutier, an Inuit leader and Nobel Peace Prize nominee **13.** Sir Richard Branson **14.** Lonnie Thompson, a prominent OSU climate researcher (and Mosley-Thompson's husband; see 2) **15.** Al Gore **16.** Wangari Muta Maathai, Kenyan founder of the Green Belt Movement **17.** Susan Solomon; she pulled together the Intergovernmental Panel on Climate Change (IPCC) report concluding that humans are the main force behind global warming **18.** Rajendra K. Pachauri, chairman of the IPCC **19.** Newt Gingrich **20.** Robert F. Kennedy Jr. **21.** Ed Begley Jr.

Climate Change Policy Debate

The End

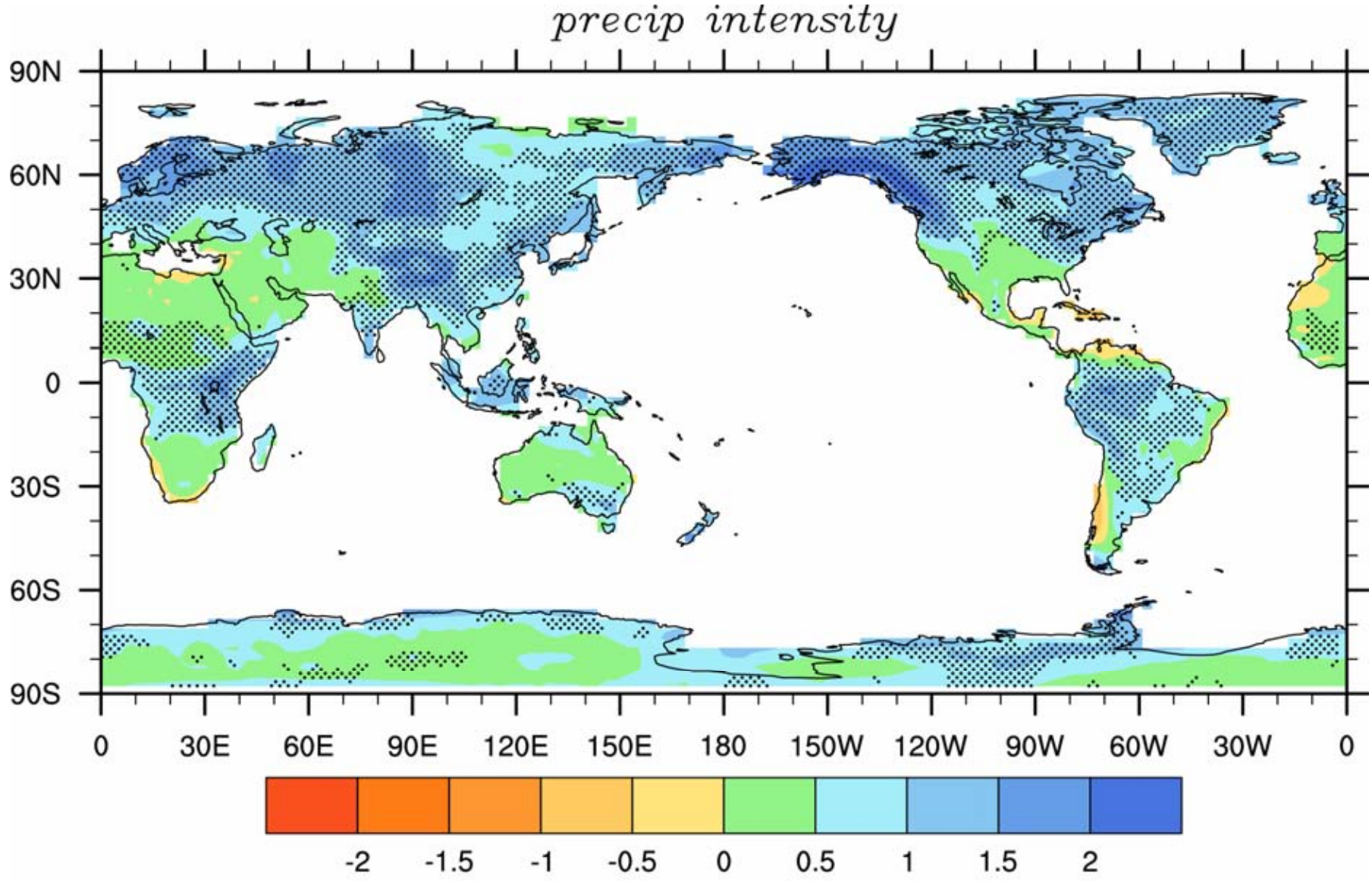


Fig. 1: The 8 member multi-model ensemble mean *precip intensity* difference from Tebaldi et al (2005) for A1B, 2080-2099 minus 1980-1999.

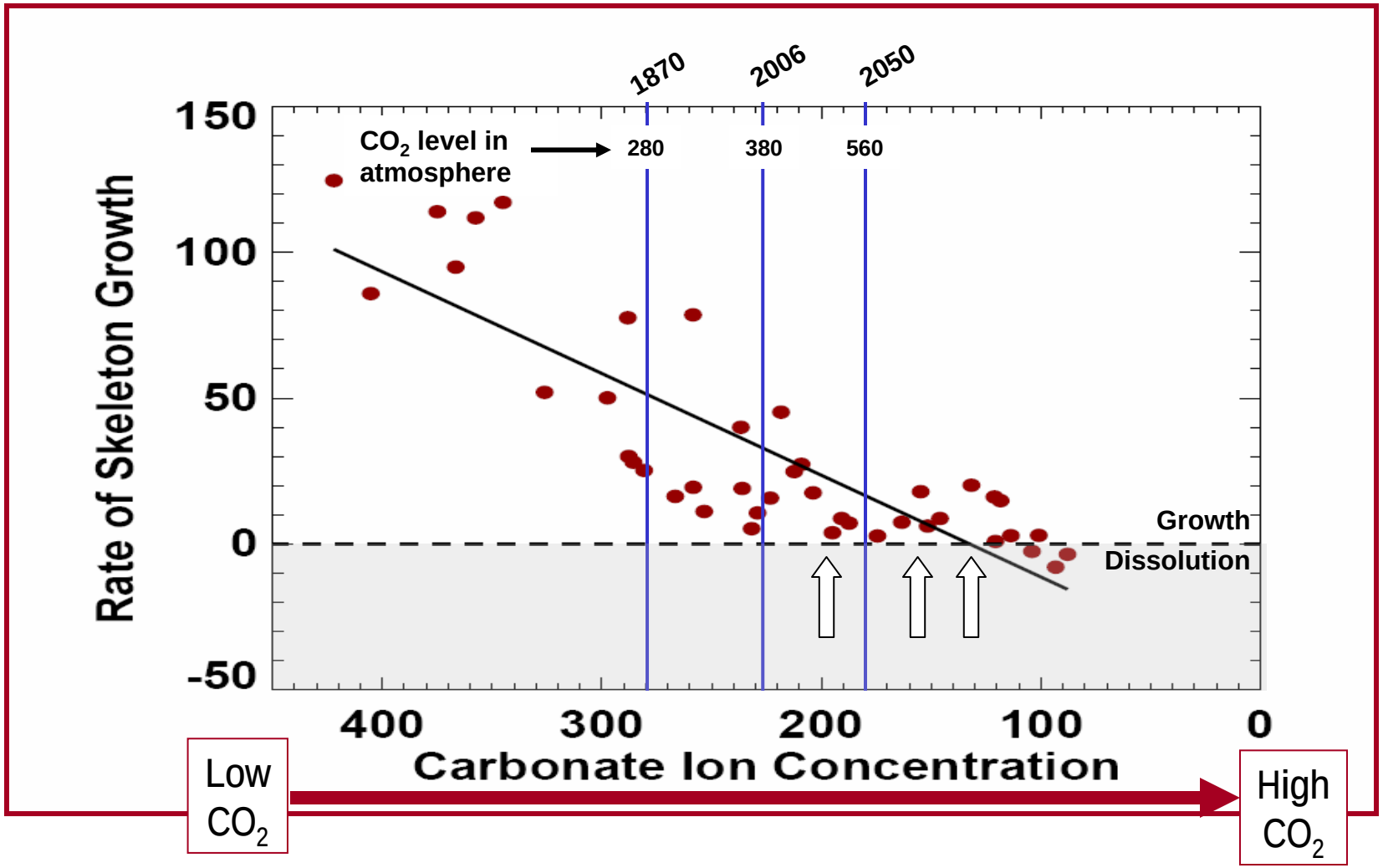
Ongoing and Future Climate Change Developments

- Higher resolution, especially important near mountains, river flow, and coast lines for some simulations
- Full hydrological coupling including ice sheets…important for sea level changes
- Continued improvement in clouds and aerosol effects including solar dimming
- Better vegetation and land surface treatments with ecological interactions
- Carbon and other biogeochemical cycles

Regional Climate Changes

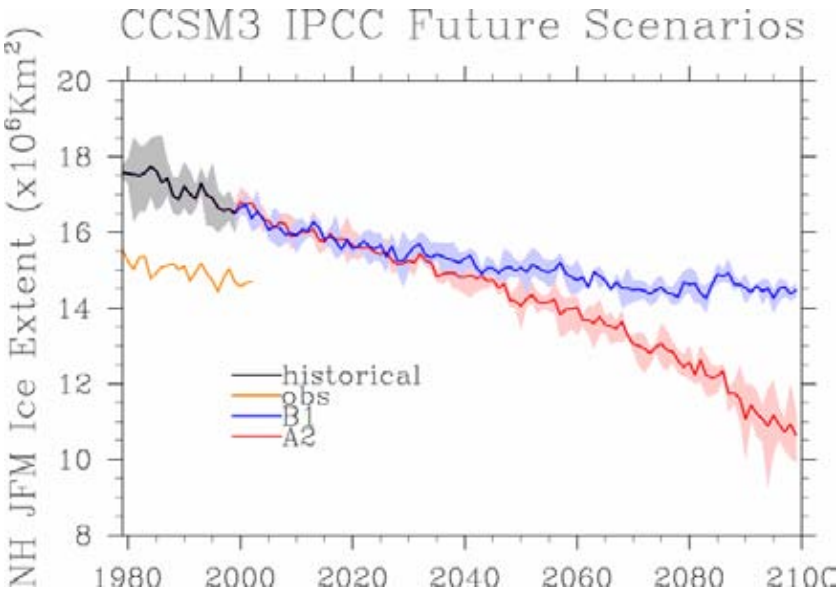
- Warmer, more moist, heavier rainfall events
- Jet stream move further poleward and weaker
- Storm systems moving slower but more intense rainfall events
- Hurricanes likely to be more intense

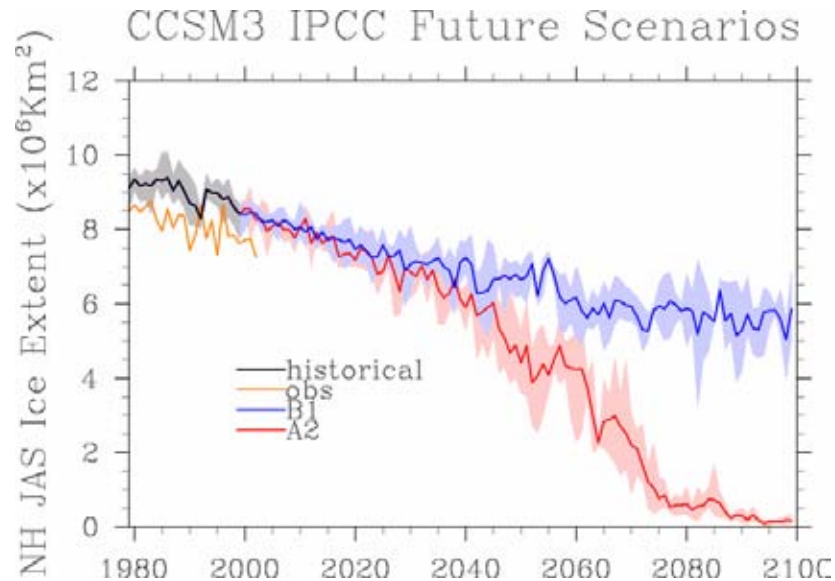
Skeletal Growth in the B2 Reef Decreased Under Future CO_2 Conditions

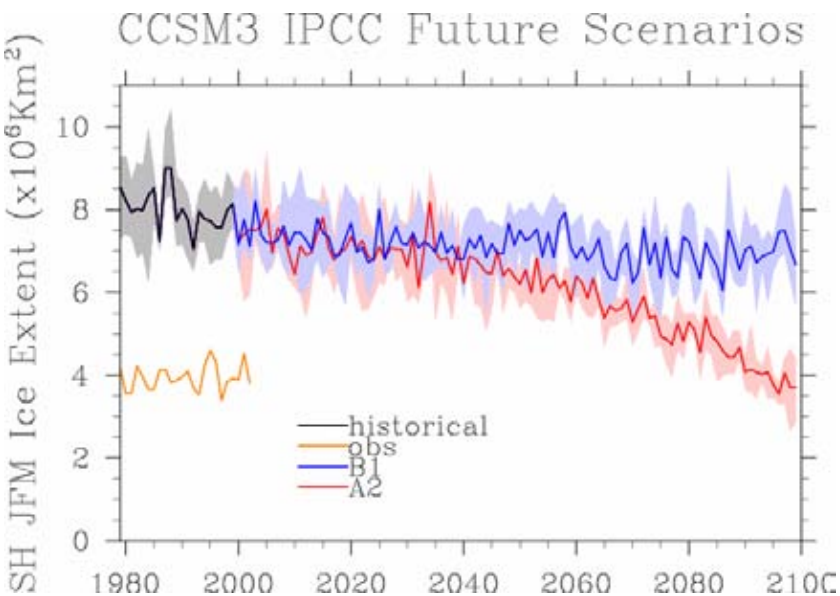


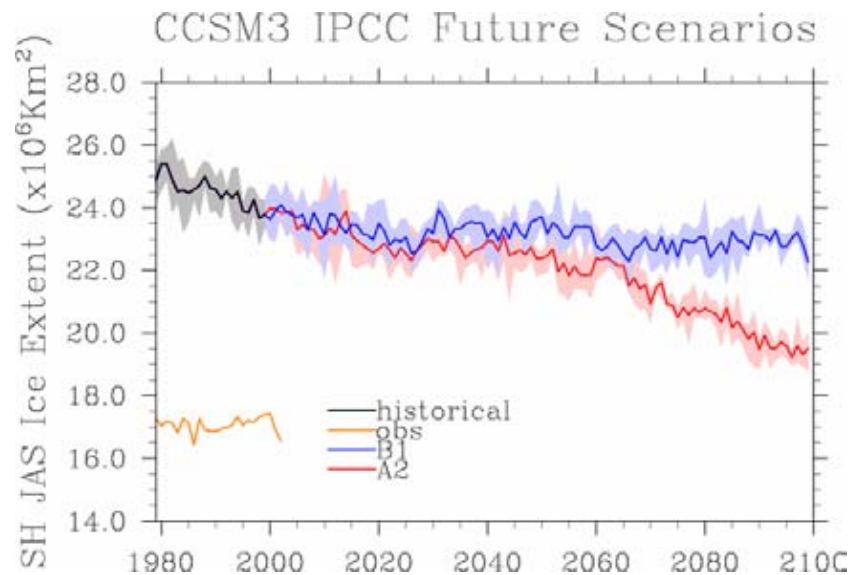
Data from Chris Langdon

Sea-ice Extent in Both NH and SH



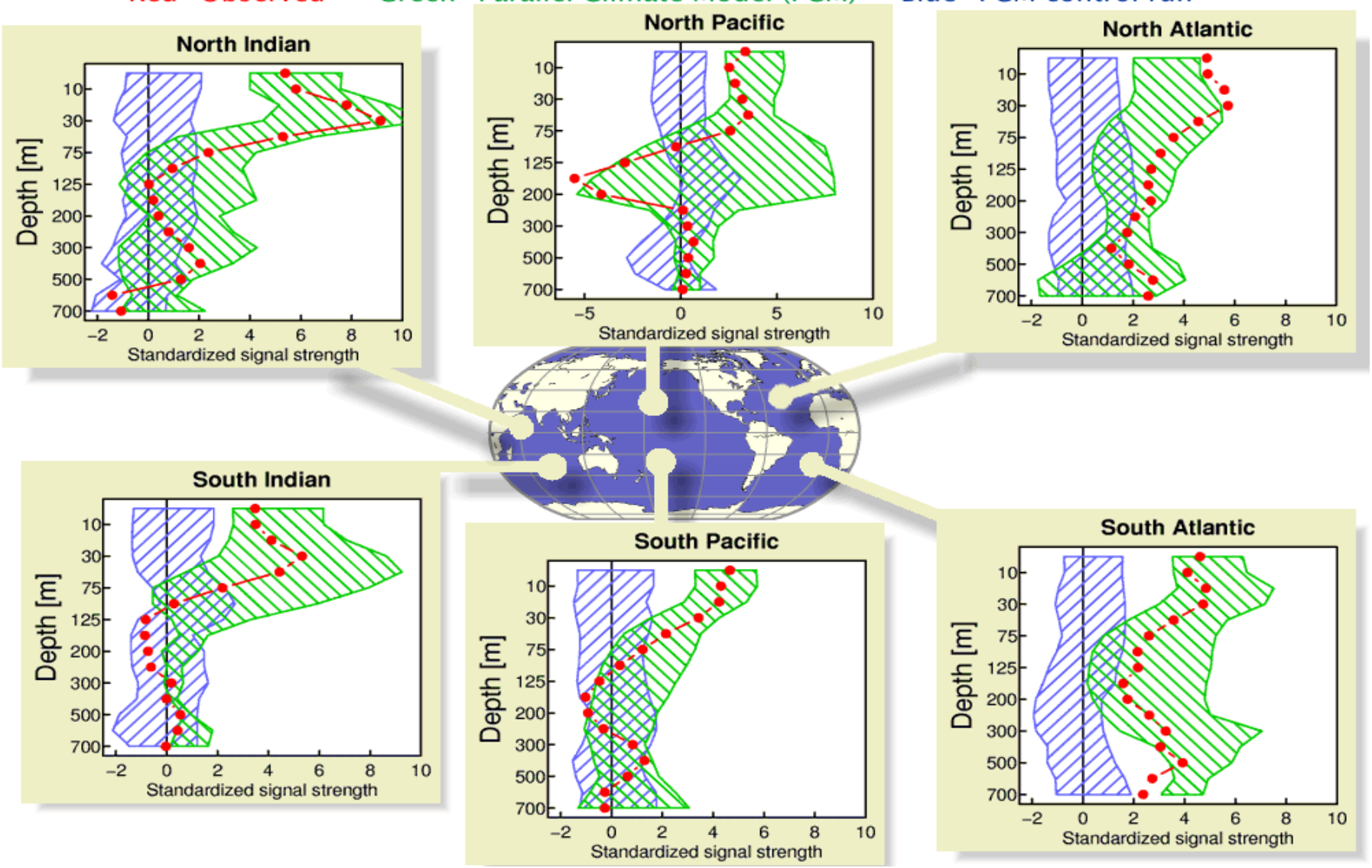






Penetration of Ocean Warming Signal (1955–1999)

Red=Observed Green=Parallel Climate Model (PCM) Blue=PCM control run

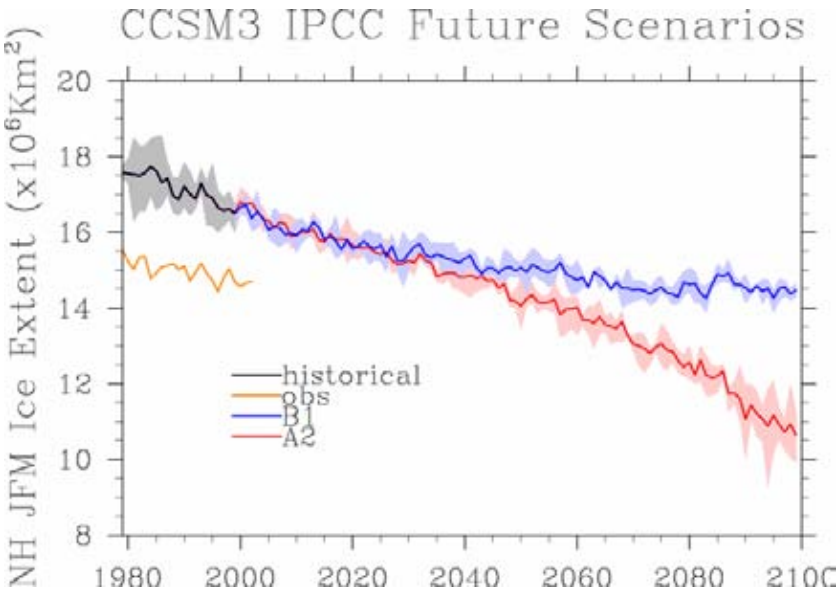


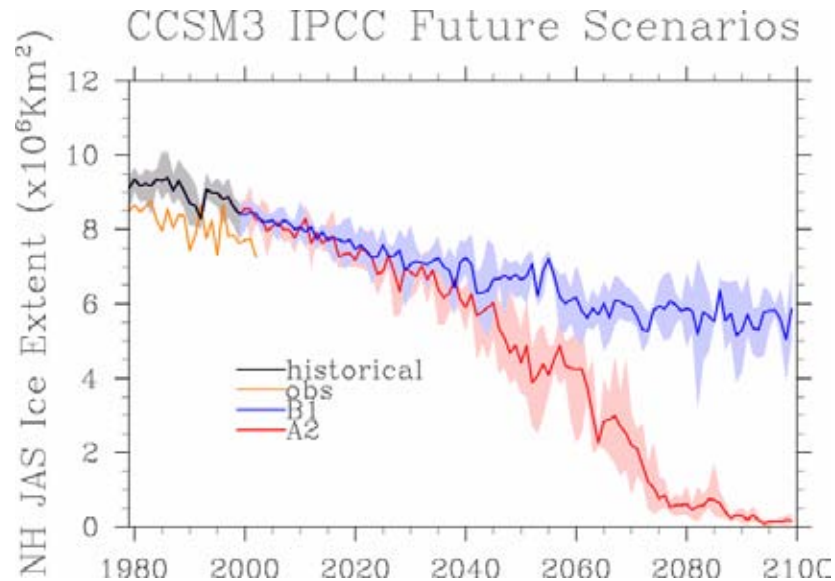
T. Barnett and D. Pierce of SIO

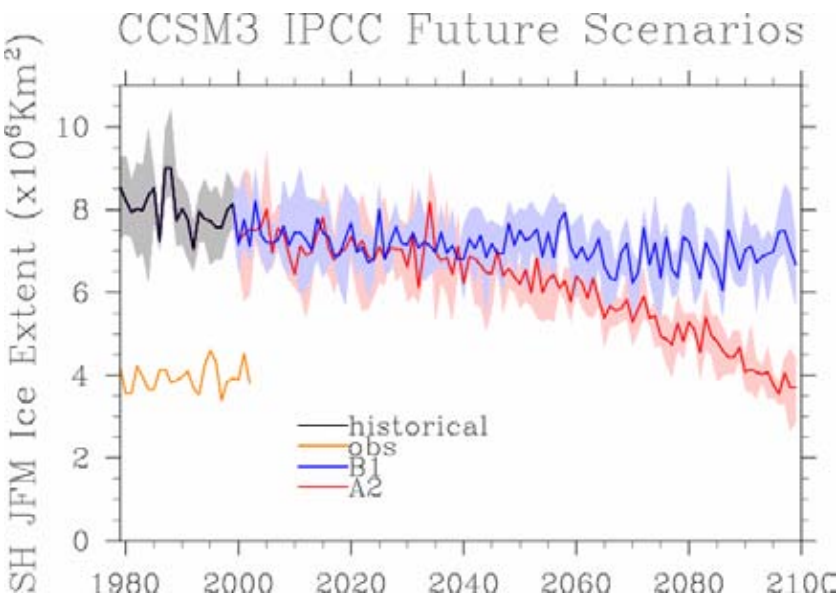
Effects of Land Cover Changes

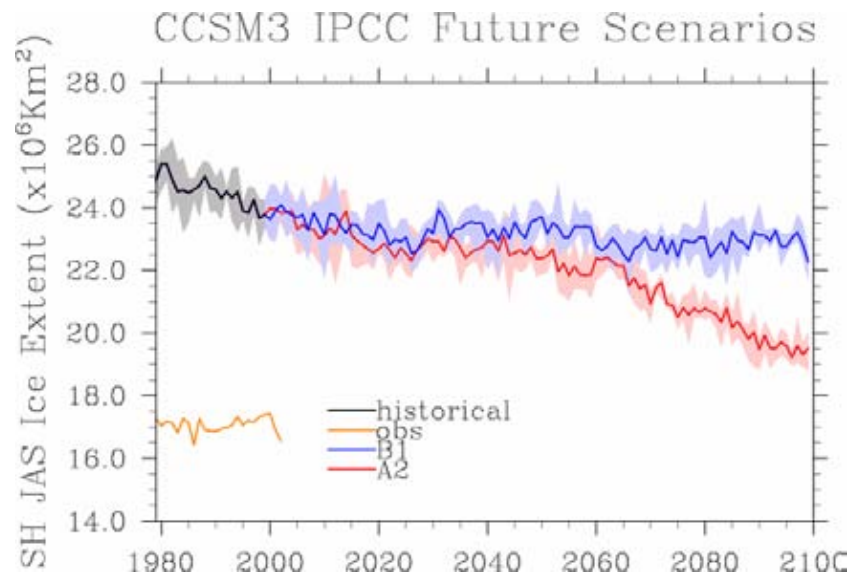
- University of Kansas has one of the few world experts… Johannes Feddema
- Smaller than the "greenhouse gas" effect but regionally important

Sea-ice Extent in Both NH and SH

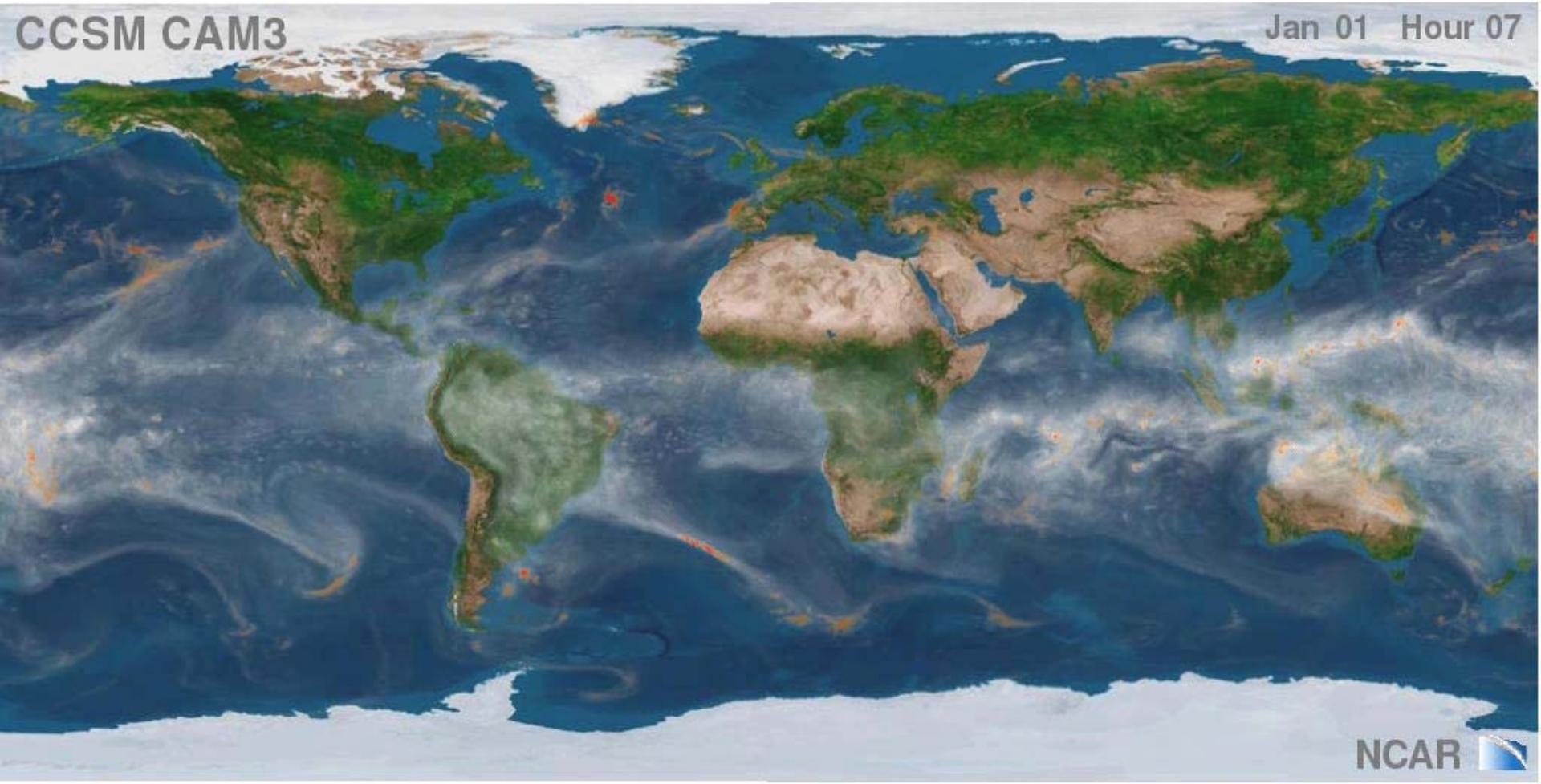








The Breakthrough NSF/DOE Collaboration on the IPCC AR4 Simulations



Lawrence Buja
National Center for Atmospheric Research
Boulder, Colorado

CAM T340- Jim Hack

The Breakthrough NSF/DOE Collaboration on the IPCC AR4 Simulations

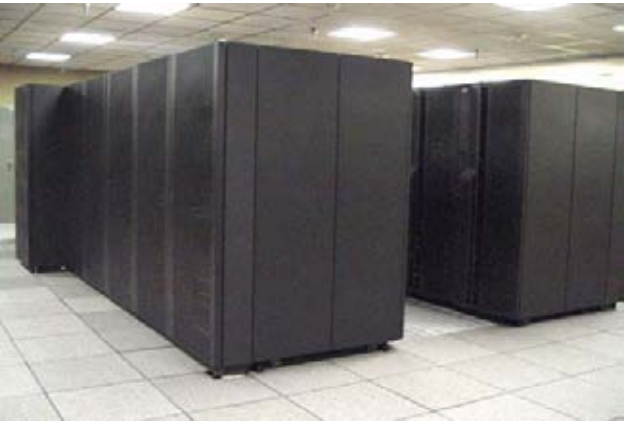
Lawrence Buja
National Center for Atmospheric Research
Boulder, Colorado

"Science exists to serve human welfare. It's wonderful to have the opportunity given us by society to do basic research, but in return, we have a very important moral responsibility to apply that research to benefiting humanity." Walter Orr Roberts

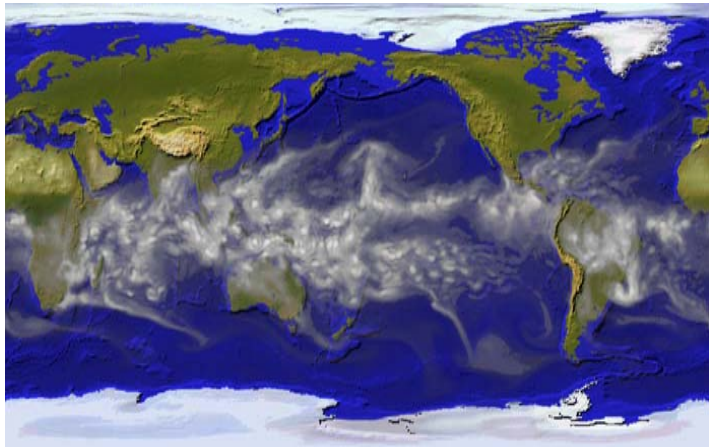
NCAR Scientific Support facilities

- National Science Foundation FFRDC
- 900 Staff, 500 Scientists/Engineers
- 4 Boulder-area campuses

1. Observational Facilities

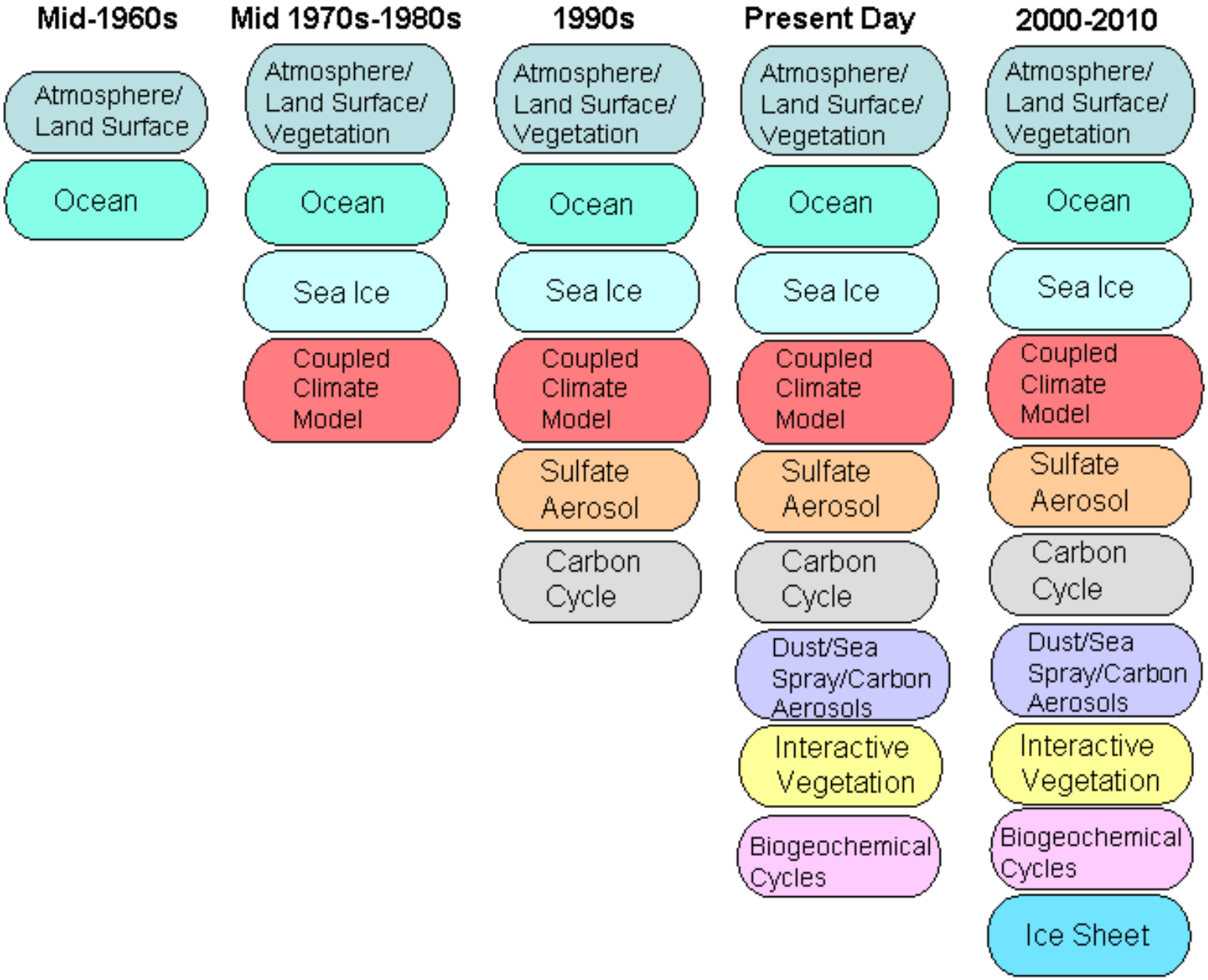


2. Supercomputer/Network Resources



3. Scientific Models

Timeline of Climate Model Development



CCSM Working Groups

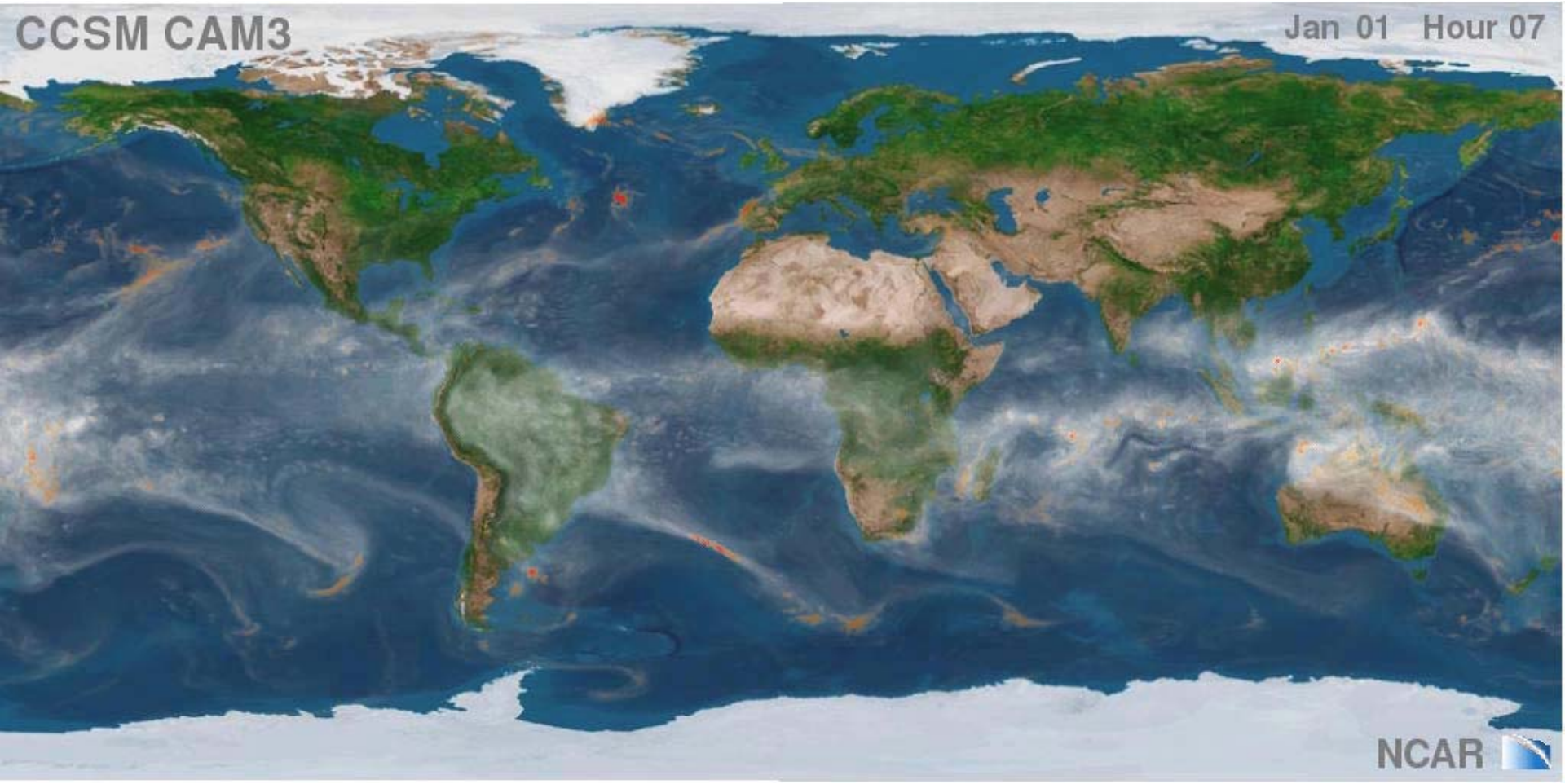
Development

- Atm Model
- Ocean Model
- Land Model
- Polar Climate
- BioGeo Chemistry
- Chemistry Climate

Application

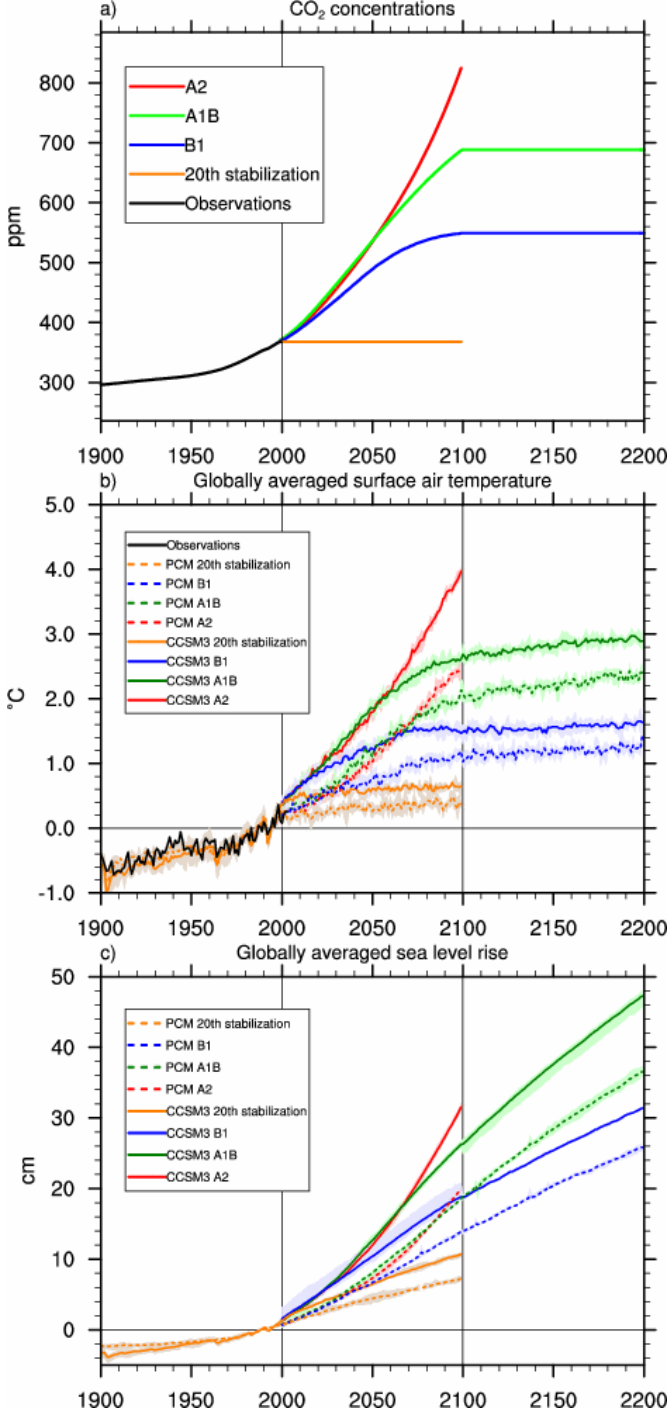
- Climate Change
- PaleoClimate
- Climate Variability
- Software Engineering

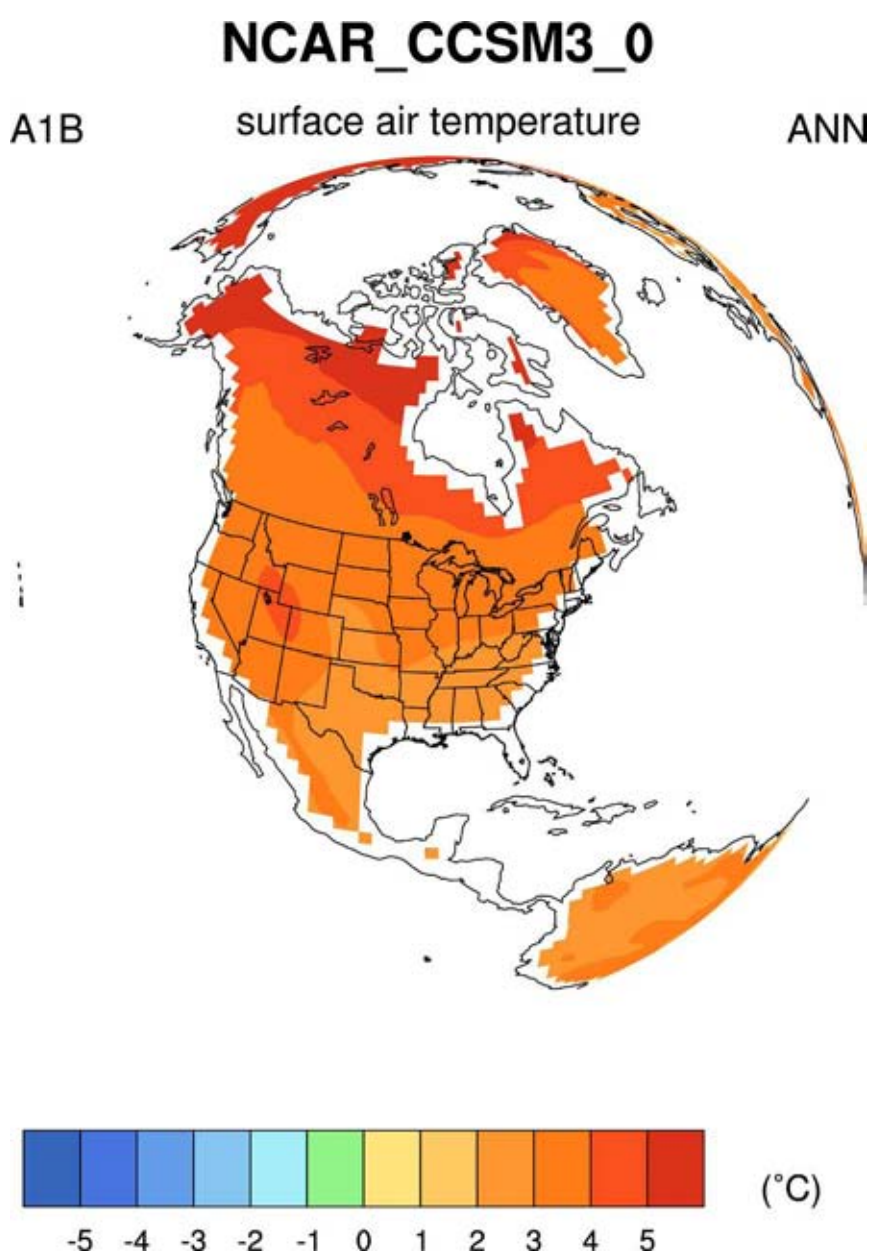
CCSM is primarily sponsored by the National Science Foundation and the Department of Energy

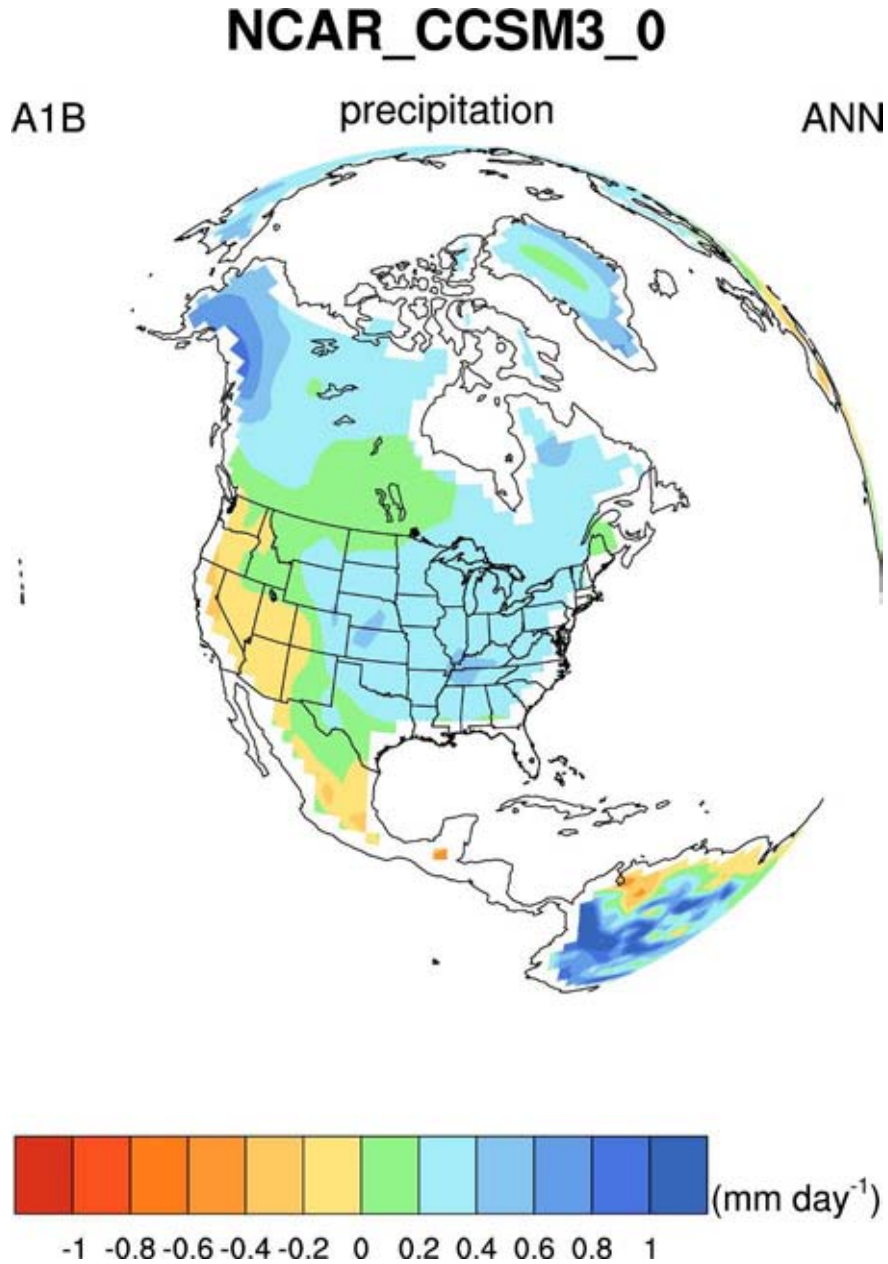

CCSM CAM3
Jan 01 Hour 07
NCAR

Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) Simulations

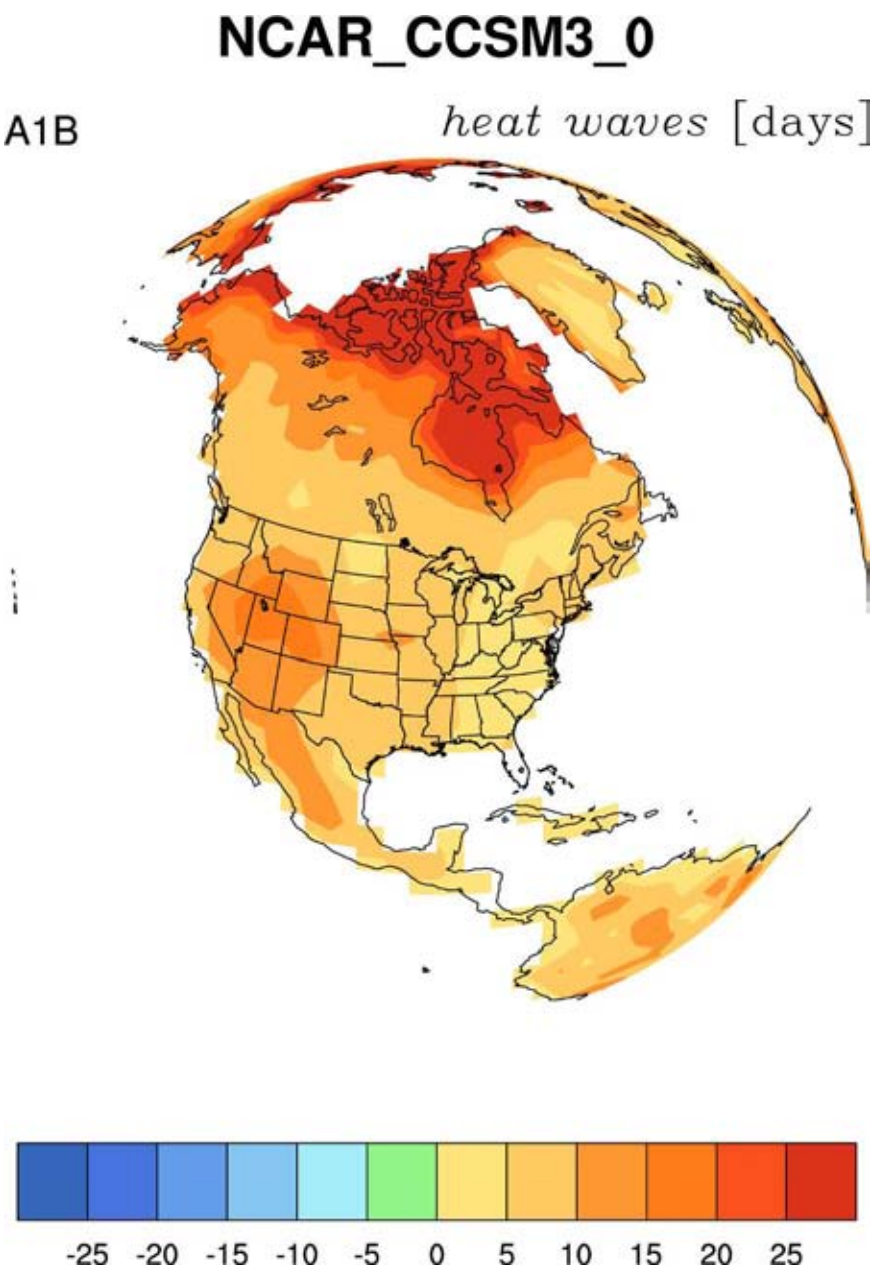
- NCAR Community Climate System Model (CCSM-3).
- Open Source
- 8-member ensembles
- 11,000 model years simulated
- “T85” - high resolution
- ~1 quadrillion operations/simulated year
- Rate of simulation: 3.5 sim. years/day
- Data volume for IPCC: ~110 TB
- Development effort: ~1 person-century

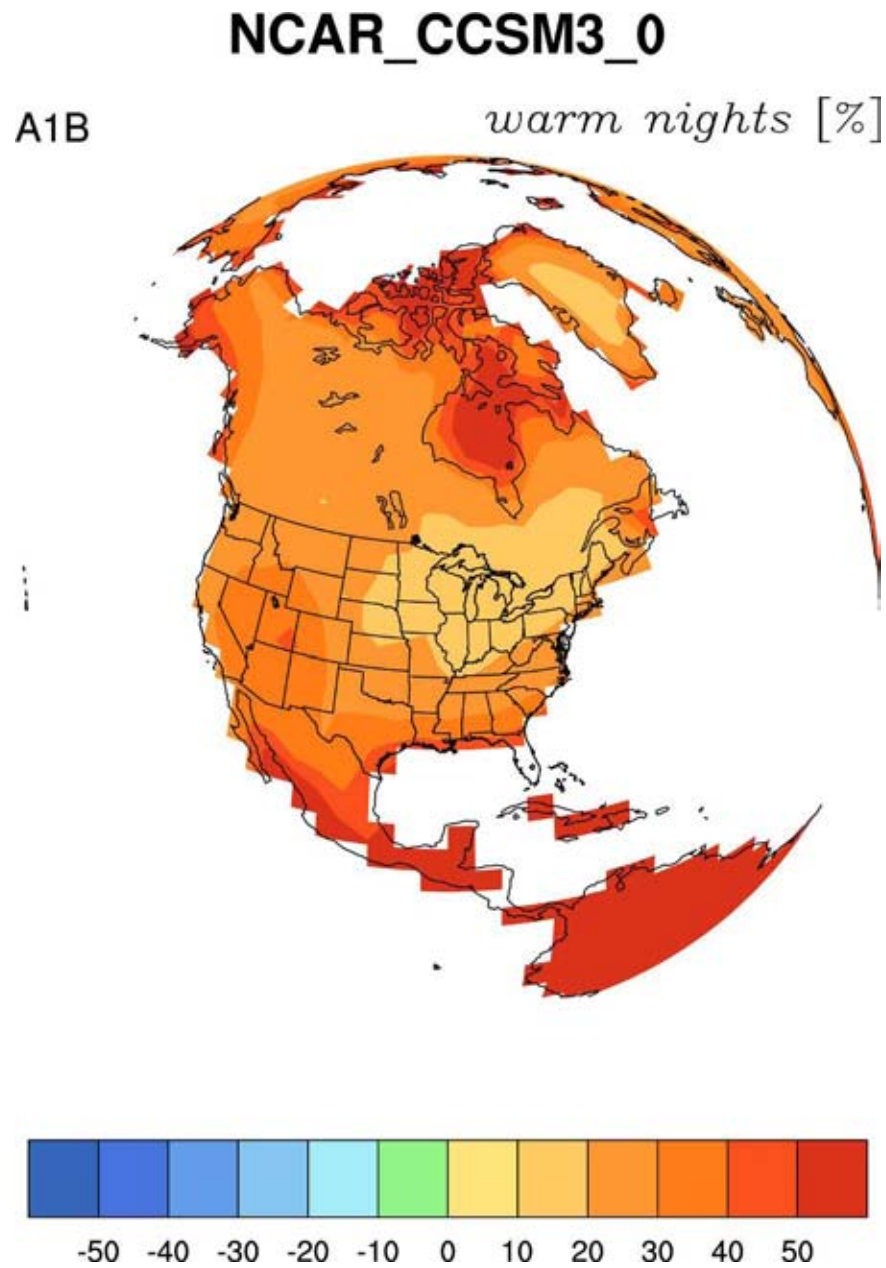






Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html





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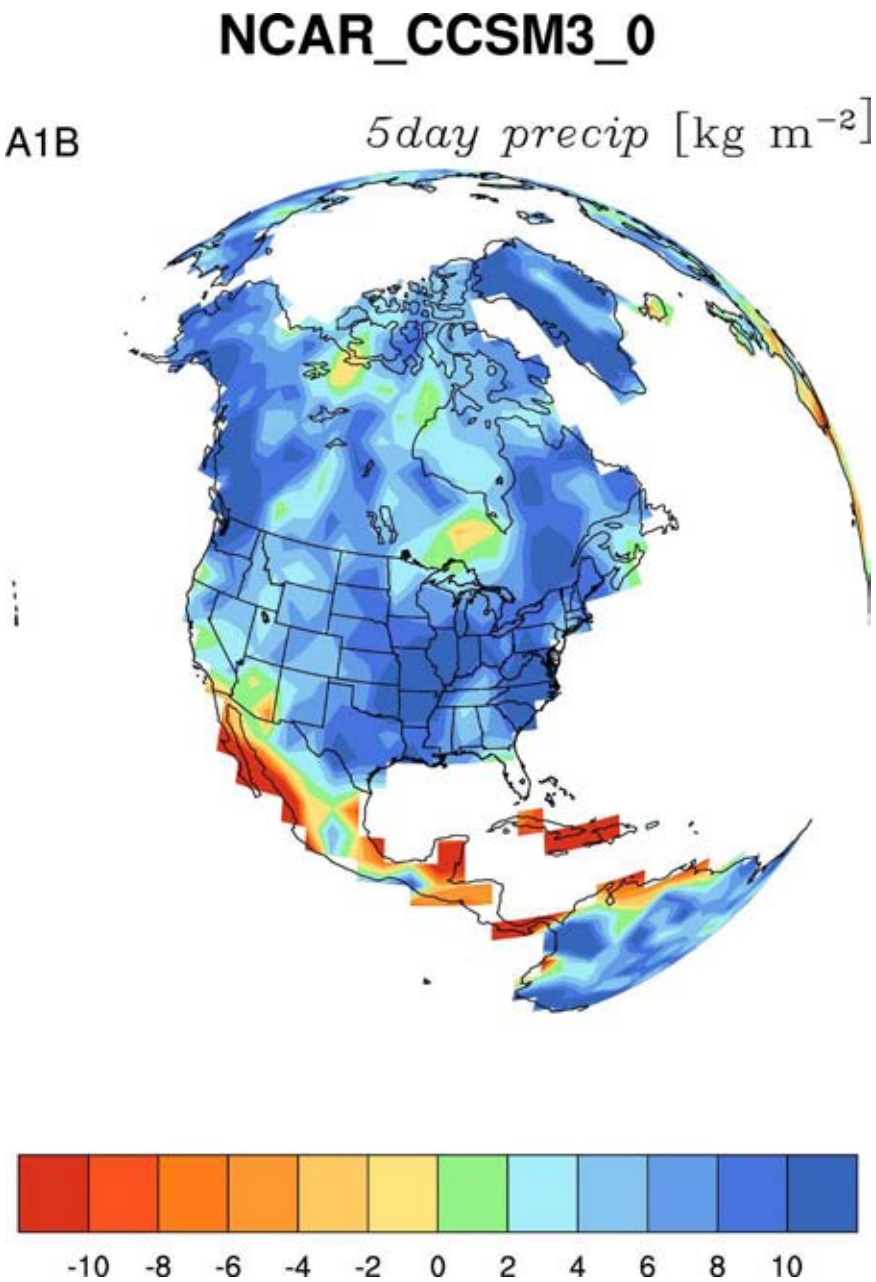

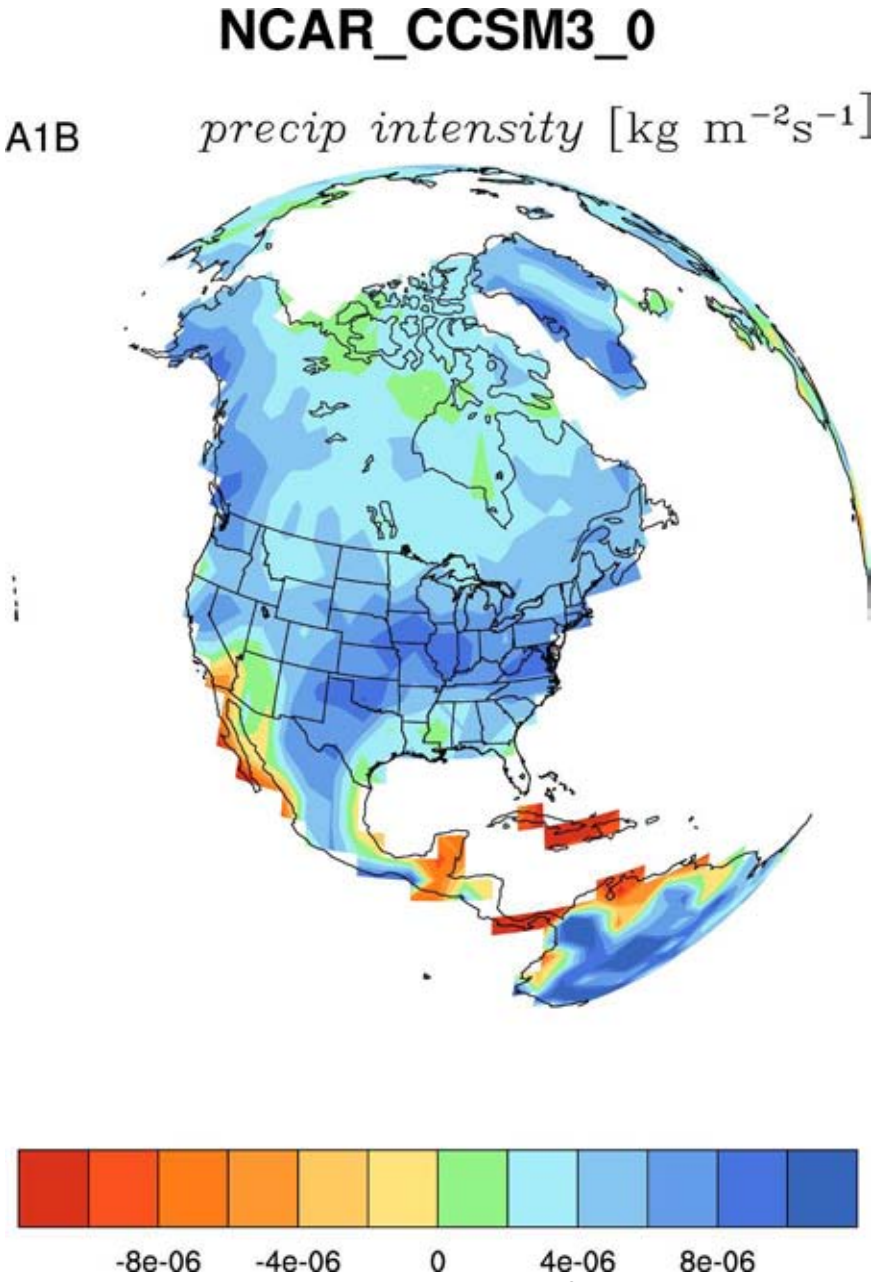

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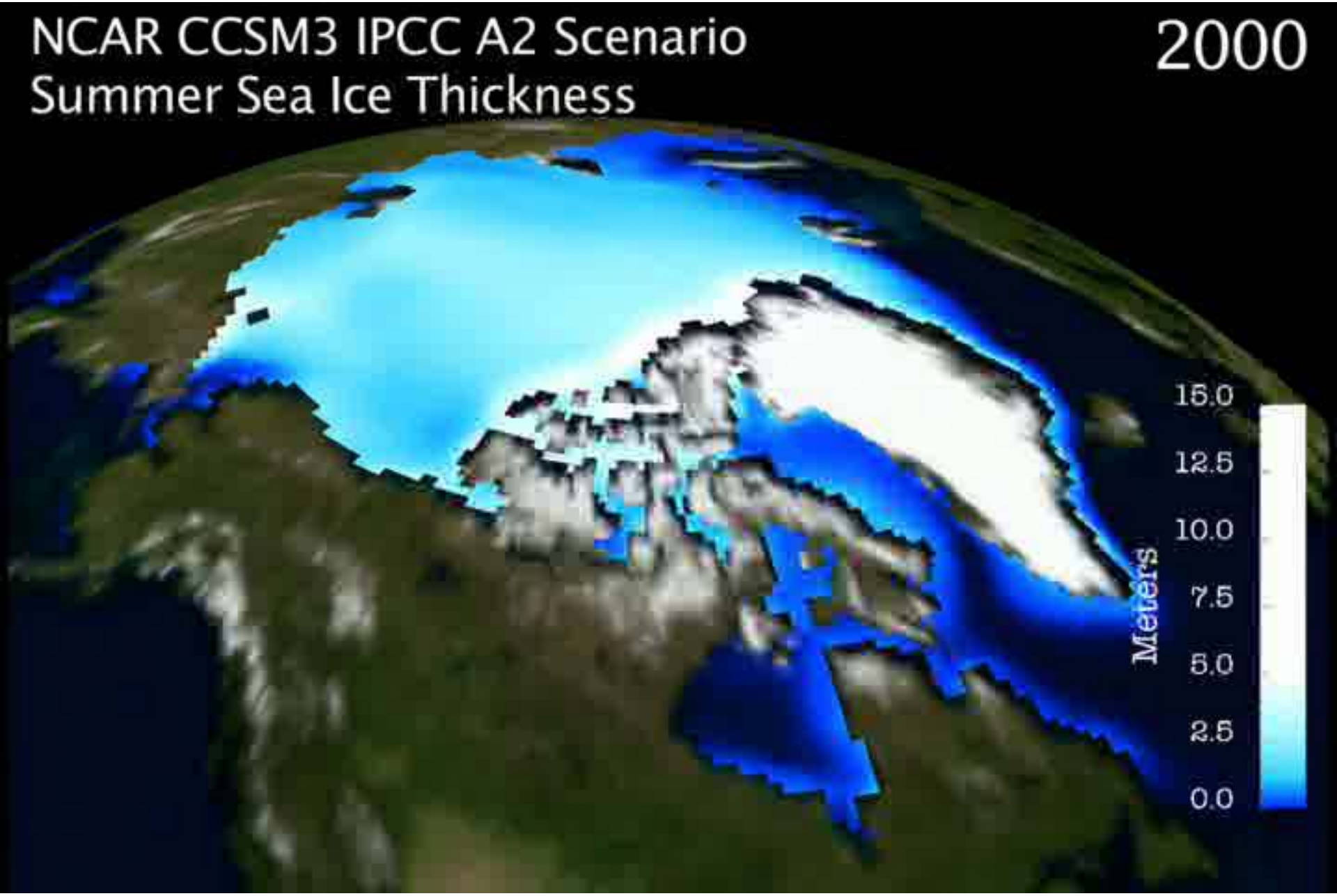
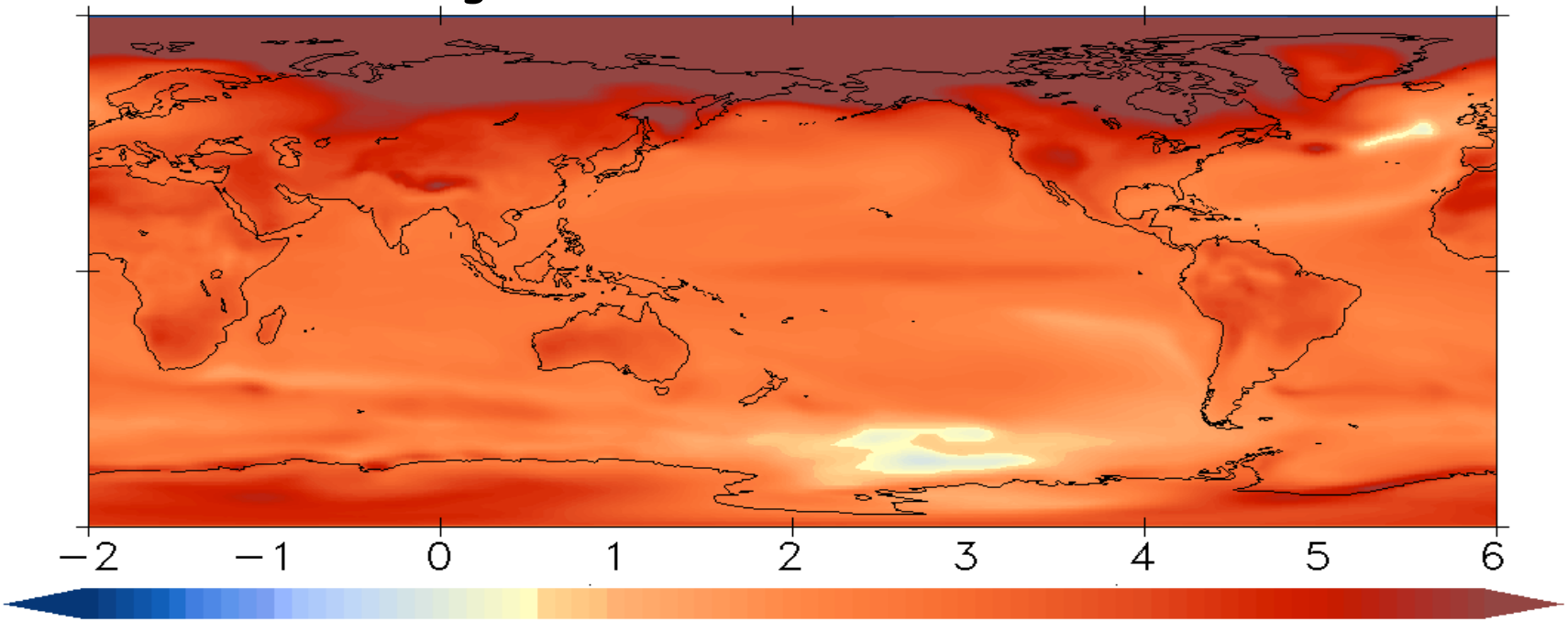
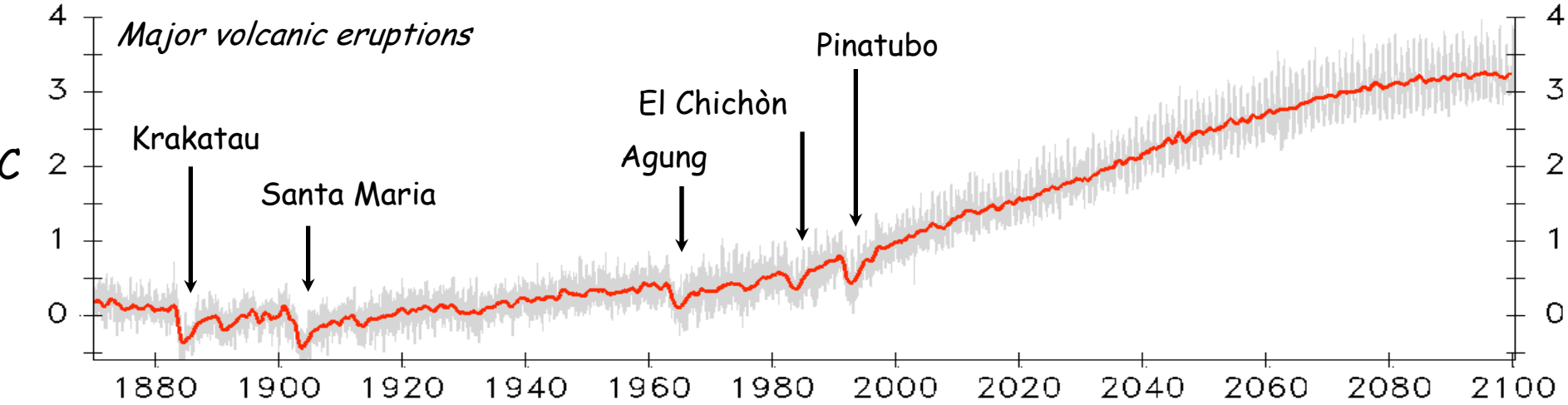

NCAR CCSM3 IPCC A2 Scenario
Summer Sea Ice Thickness
2000
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Meters

The Public is now engaging at a level never seen before

A1B °C change relative to 1870-1899 baseline

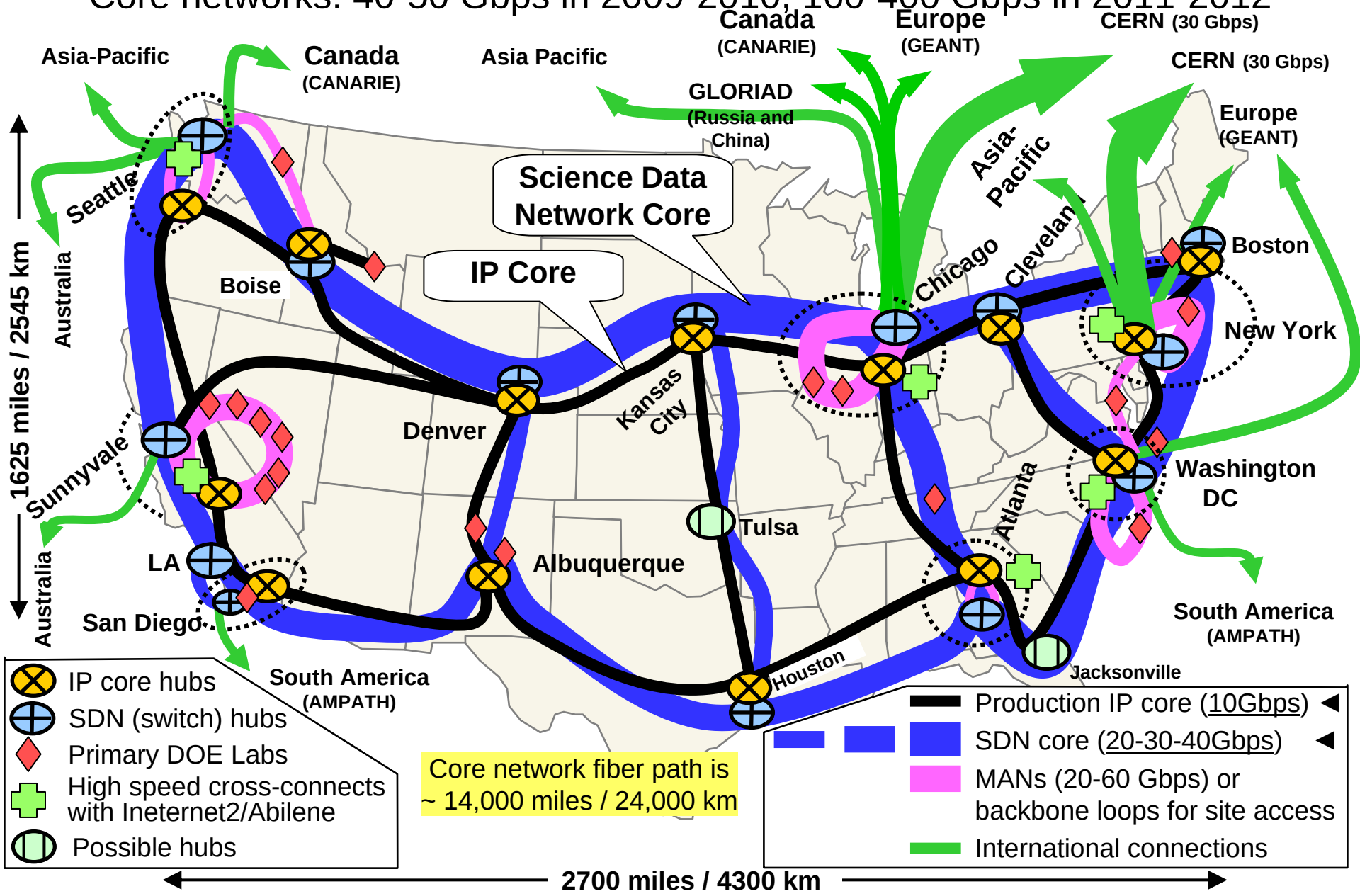




Global average surface temperature (relative to 1870-1899 mean)

DOE ESnet4 Configuration

Core networks: 40-50 Gbps in 2009-2010, 160-400 Gbps in 2011-2012



Climate Modeling Basics

The IPCC AR4 Simulations and Report

Geoengineering

Next steps

DOE CCRD Directions

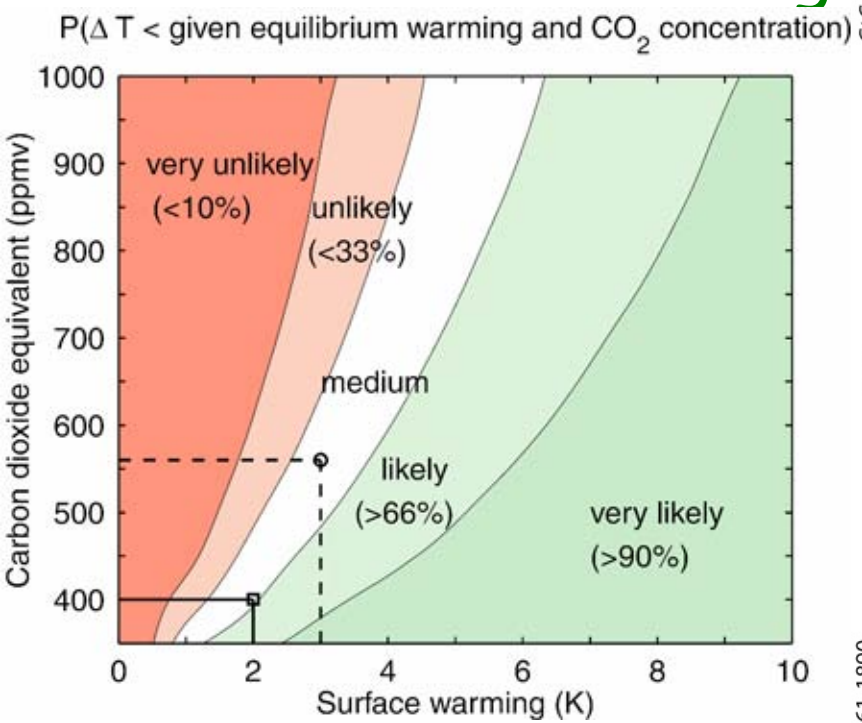
- Less emphasis on climate change detection and attribution
- More emphasis on decision support for policy makers
  - provide decision-makers with scientific information on "acceptable" target levels for stabilizing atmospheric CO_2
  - possible adaptation and mitigation strategies for the resulting climates before or after stabilization.

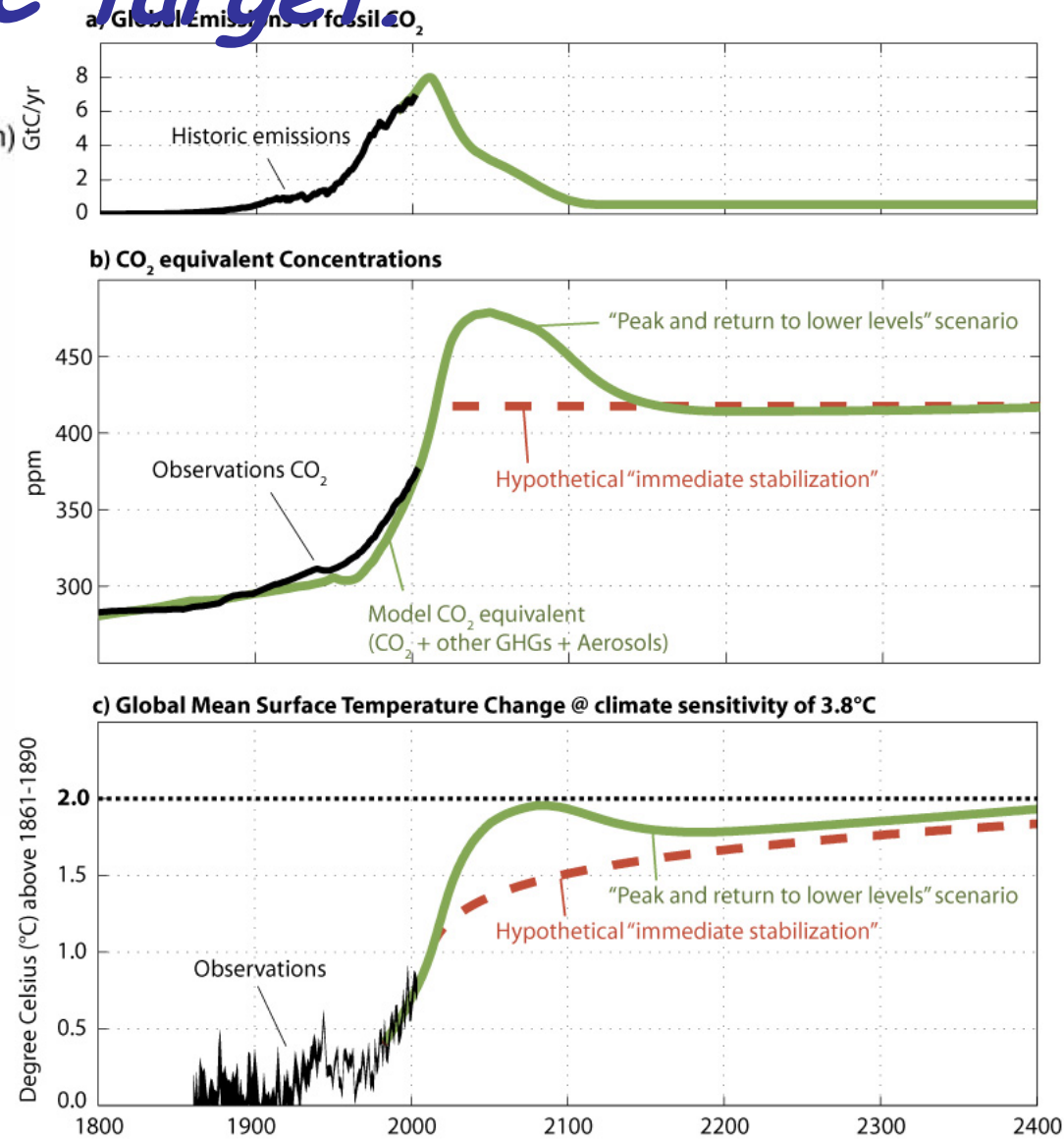
Areas

1. Advance climate & Earth systems modeling
2. Improve understanding and model representations of climate and Earth system processes that can affect climate
3. Improve understanding of human impacts and consequences of climate change
4. Improve capabilities and infrastructure for conducting climate change research

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

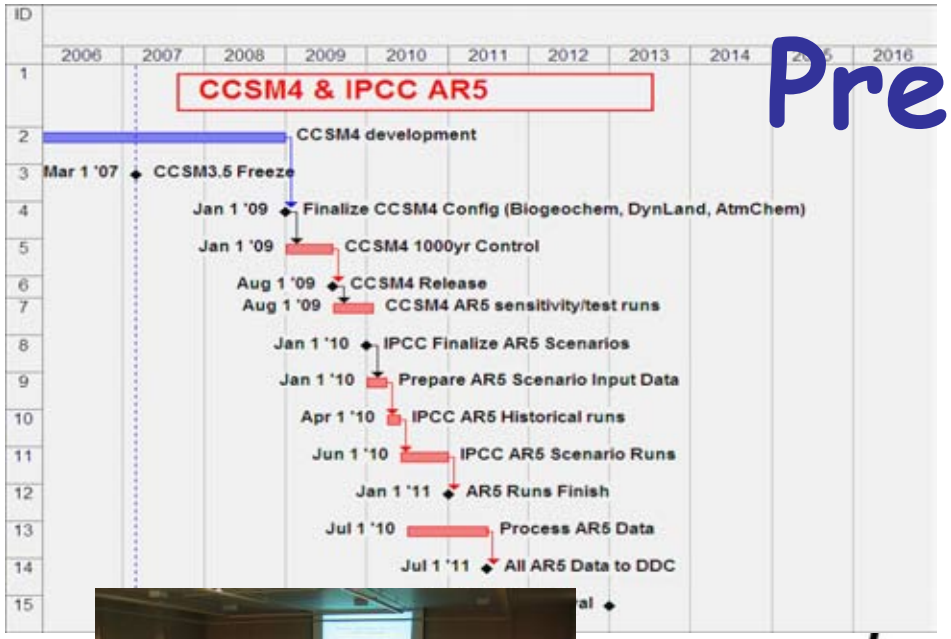
Likelihood of warming

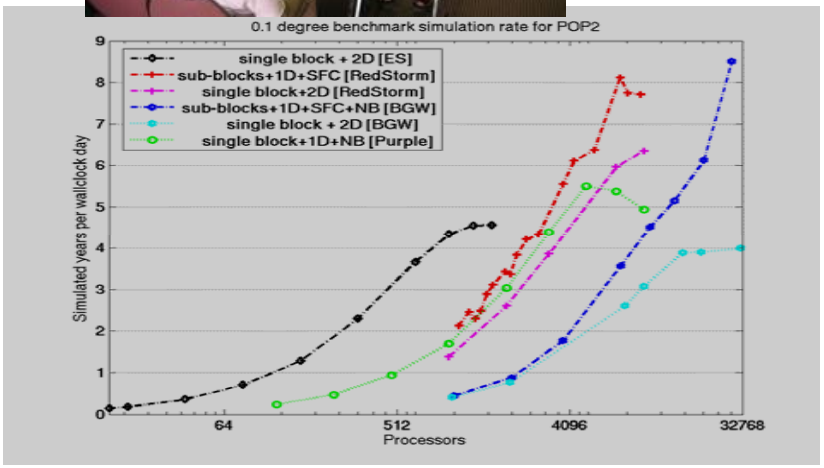




- Stabilizing temperature requires stabilizing atmospheric CO2,
- Limiting warming to 2°C requires stabilization at 400-450ppm CO2

Preparing for IPCC AR5





CCP/CCWG Research 2007-2012
2007.02.28

2008
- 1000 year CCSM4
- BGC Control Run

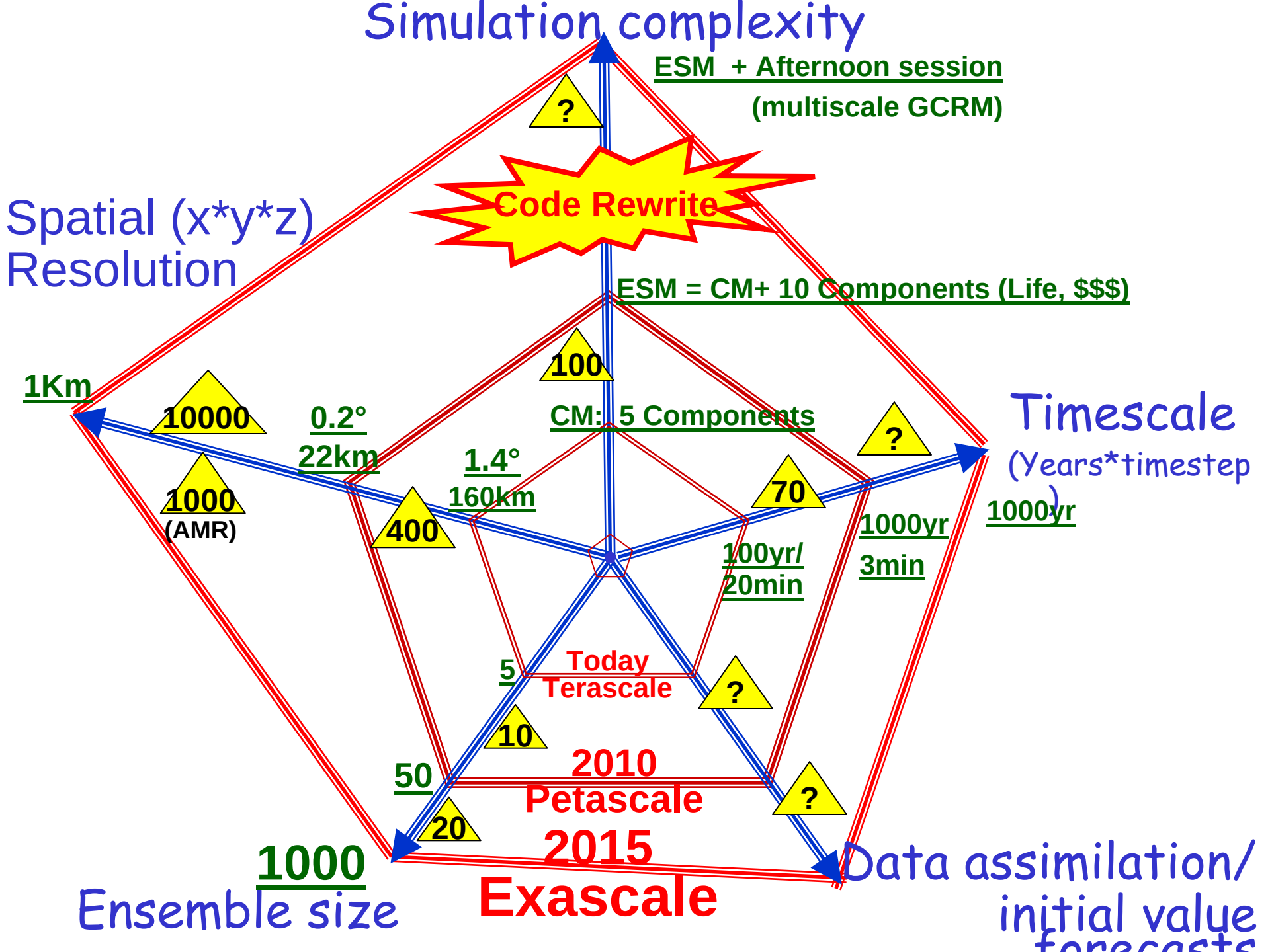
- NCAR: Analysis of climate variability: water cycle, Arctic & North Atlantic Oscillation,
- NERSC: 1000 Year CCSM4 Biogeochemistry Control Run: Carbon & nitrogen cycles + Dynamic vegetation with BGCWG
- ORNL: Climate Change to 2100 and beyond: Targeted mitigation/adaptation simulations
- ORNL: Sulfate indirect forcing
- ORNL: Prognostic carbon aerosol forcing
- ORNL: High-resolution future simulations with 0.5Atm
- ORNL: Special DOE Scenarios for future US energy strategies

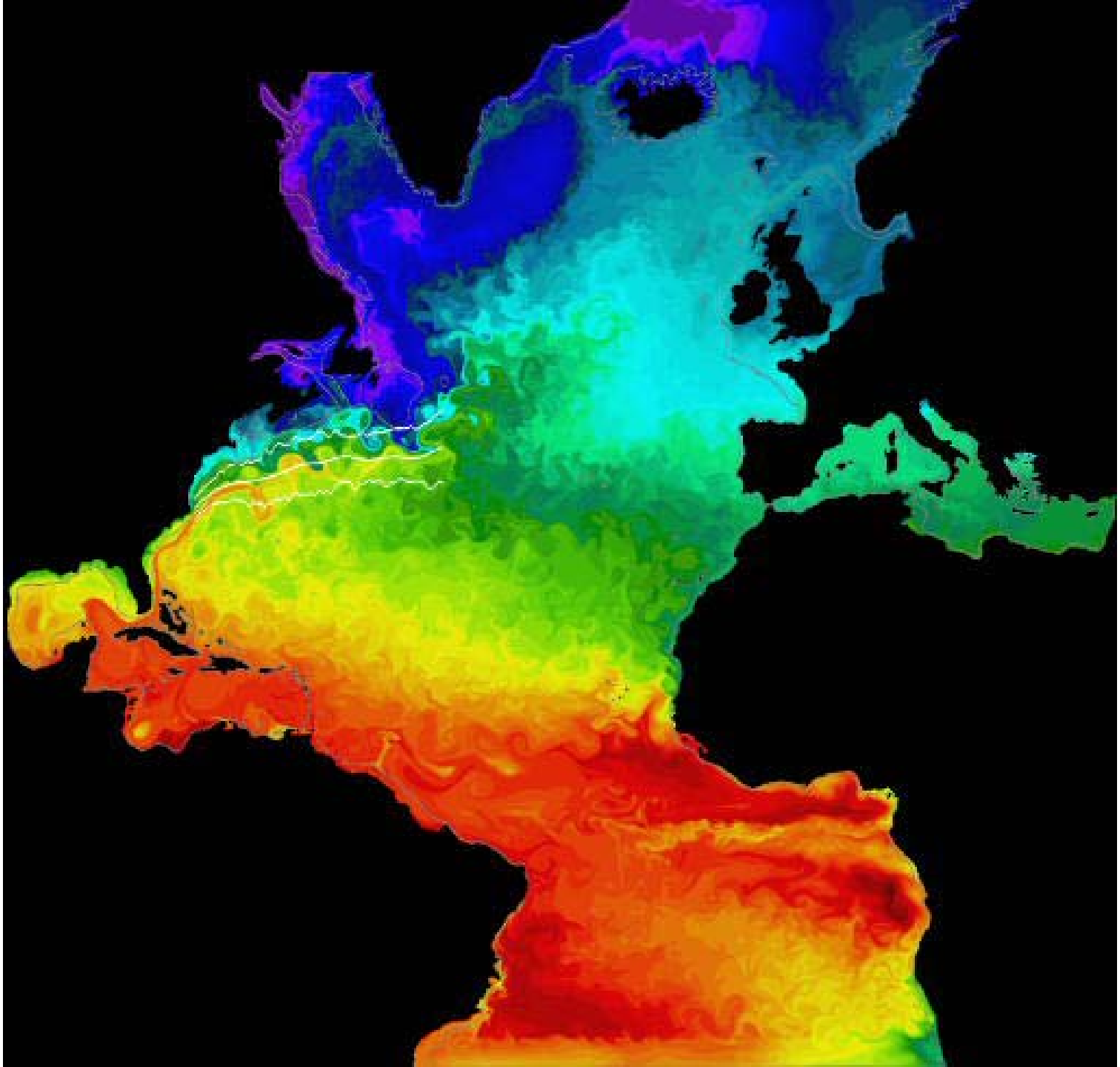
2009
- CCSM4 Release
- AR5 preparation

- NCAR: Analysis of climate variability: Climate change detection/attribution, forced vs unforced decadal variability
- NERSC: Prepare for AR5 Simulations
- ORNL: Ultrahigh-resolution 1870 control at 0.2°Atm x 0.1°Ocn
- ORNL: Special DOE Scenarios for future US energy strategies

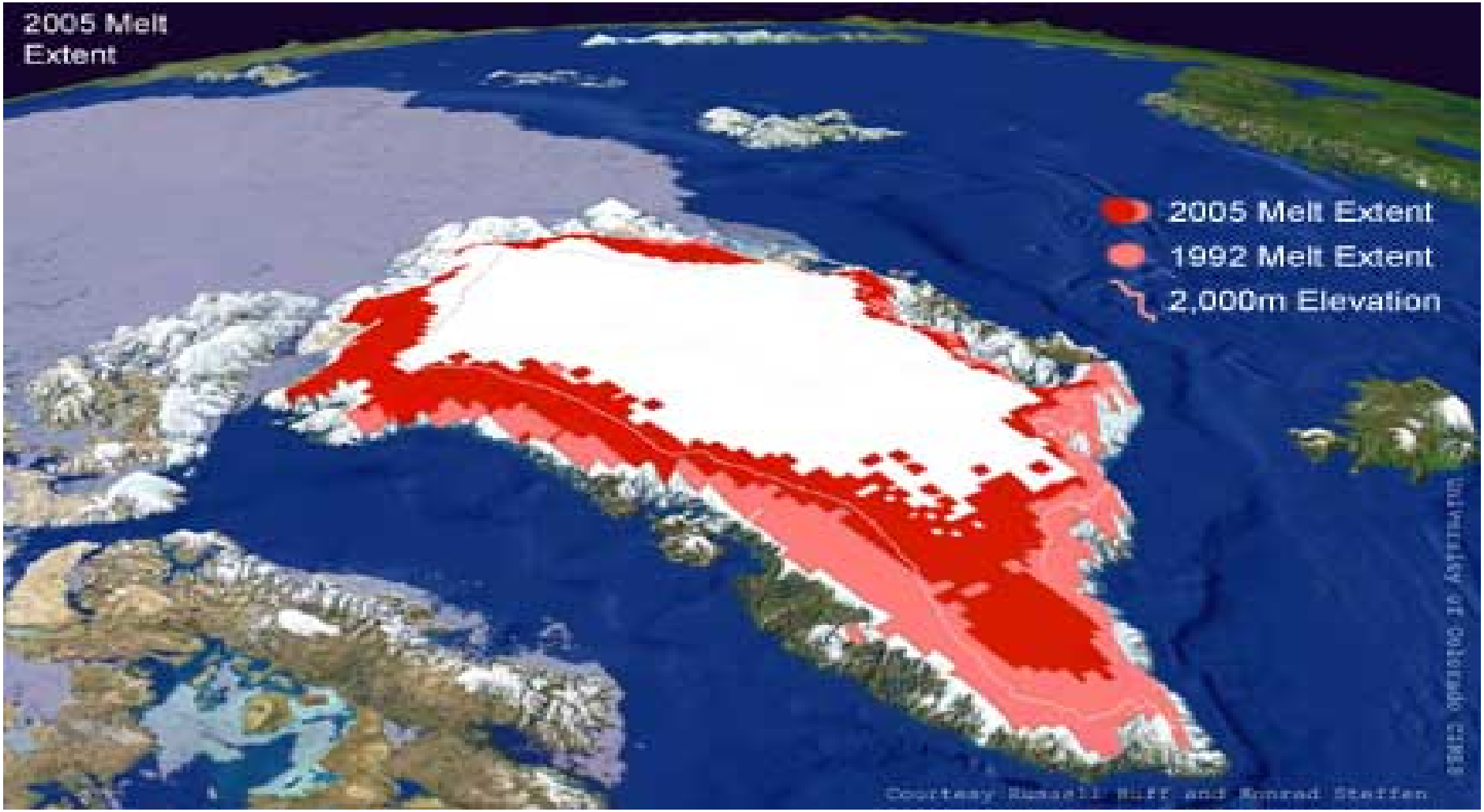
2010-2012
- IPCC AR5 runs

- ALL: IPCC AR5 Simulations
- NCAR: Analysis of climate variability: Monsoons & monsoon breakdown threshold: Role of Black Carbon & carbon aerosols Forced vs unforced decadal variability
- NERSC: Geographic representations of probabilistic climate change
- ORNL: Ultrahigh-resolution historical simulations at 0.2°Atm x 0.1°Ocn
- ORNL: Special DOE Scenarios for future US energy strategies

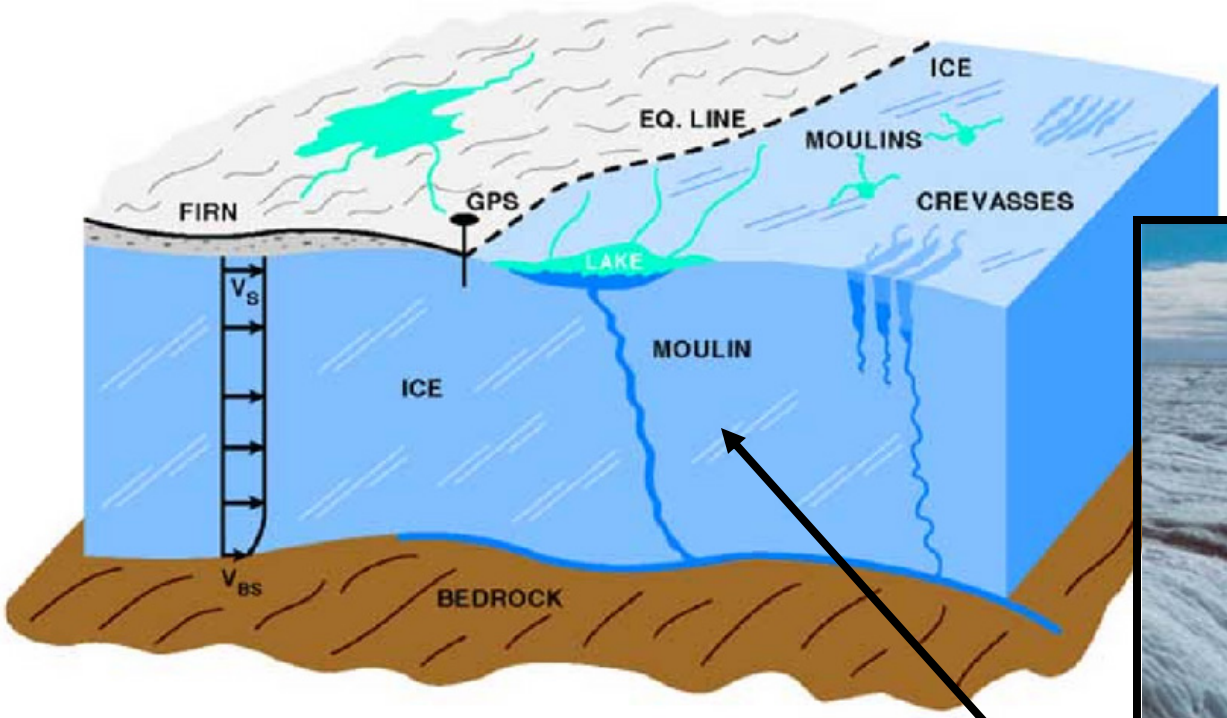

Simulation complexity
ESM + Afternoon session
(multiscale GCRM)
?
Code Rewrite
Spatial (x*y*z) Resolution
ESM = CM+ 10 Components (Life, $$$)
100
1Km
10000
0.2°
22km
CM: 5 Components
?
Timescale
(Years*timestep)
1000
(AMR)
400
1.4°
160km
70
1000yr
1000yr
100yr/
20min
3min
5
Today
Terascale
?
10
50
2010
Petascale
?
20
2015
Exascale
1000
Ensemble size
Data assimilation/
initial value
forecasts



Un.of Colorado: Cooperative Institute for Research in Environmental Science, NOAA, NASA Konrad Steffen's group uses QuickSCAT data



Multiple new dynamic mechanisms for increased ice sheet sensitivity to surface warming have been discovered



Zwally *et al*., (2002) *Science*
Alley *et al.* (2005) *Science*