What’s So Hard About Simulating Earth's Climate System?

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Outline

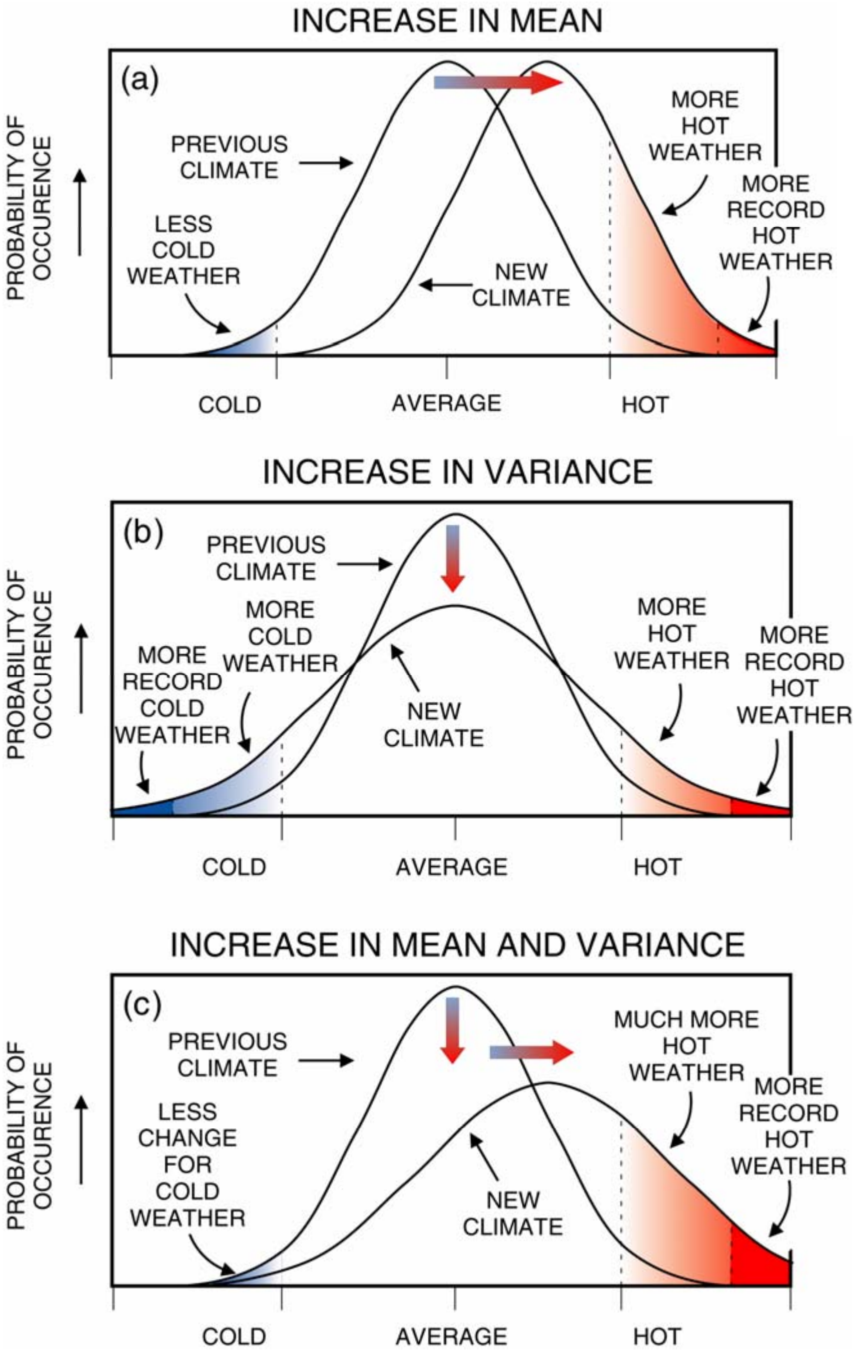
- Overview of the problem
- Characterize the approach to the problem
  - illustrate issue of truncation
  - illustrate uncertainties associated with non-resolvable motion field
  - illustrate the likely importance of scale interaction
- Show why resolution is only part of the problem
  - a necessary but not sufficient condition to reduce uncertainties
  - introduction of chemical and biogeochemical extensions needed
- Some paths forward
  - many paced by the efficient application of HPC technologies

What is Climate?

A. Average Weather
B. Record high and low temperatures
C. The temperature range
D. Distribution of possible weather
E. Extreme events

All of the above!

Climate change
and its manifestation
in terms of weather
(climate extremes)



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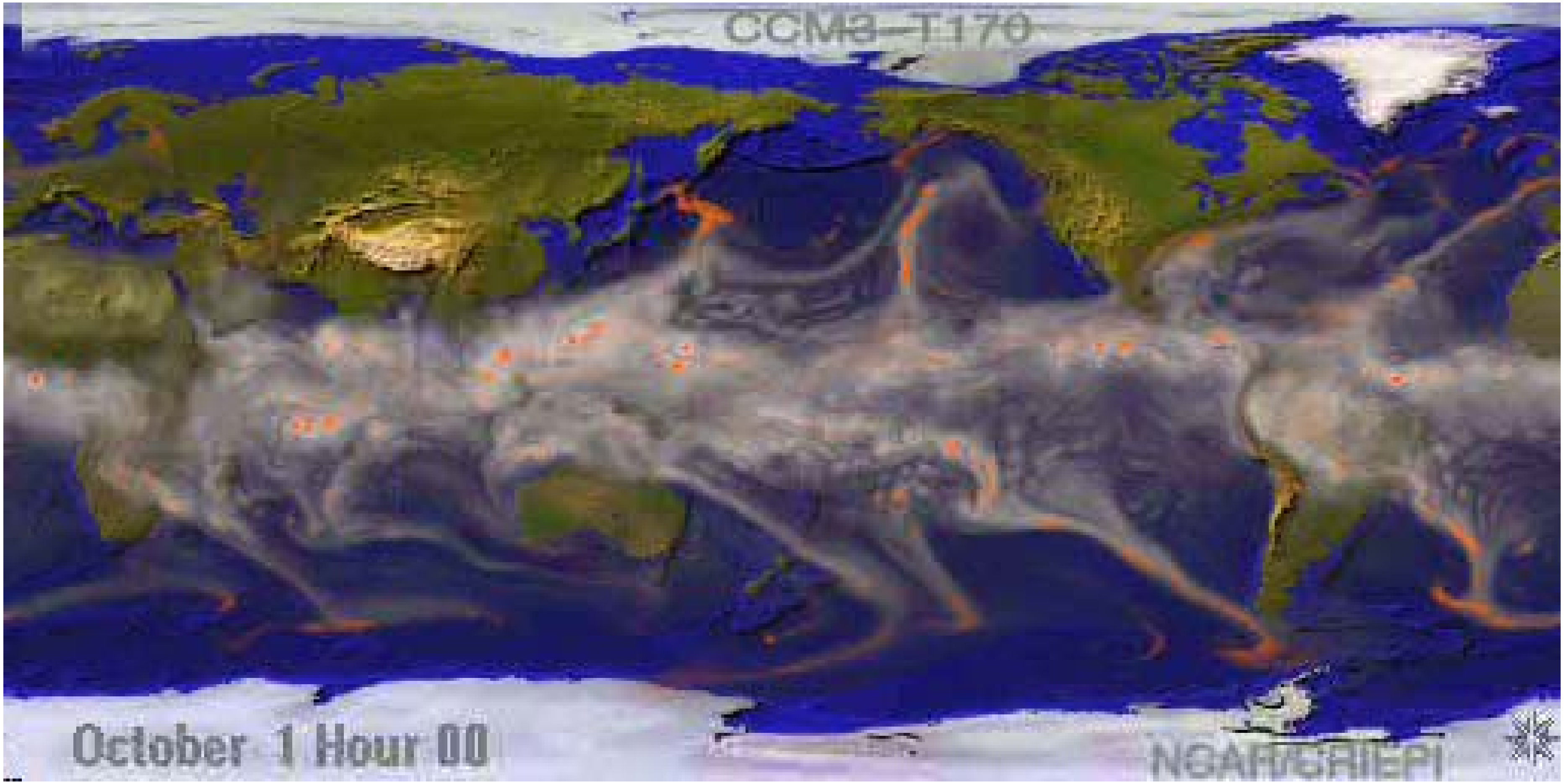
Example of Global Climate Model Simulation

Precipitable Water (gray scale) and Precipitation Rate (orange)



Animation courtesy of NCAR SCD Visualization and Enabling Technologies Section

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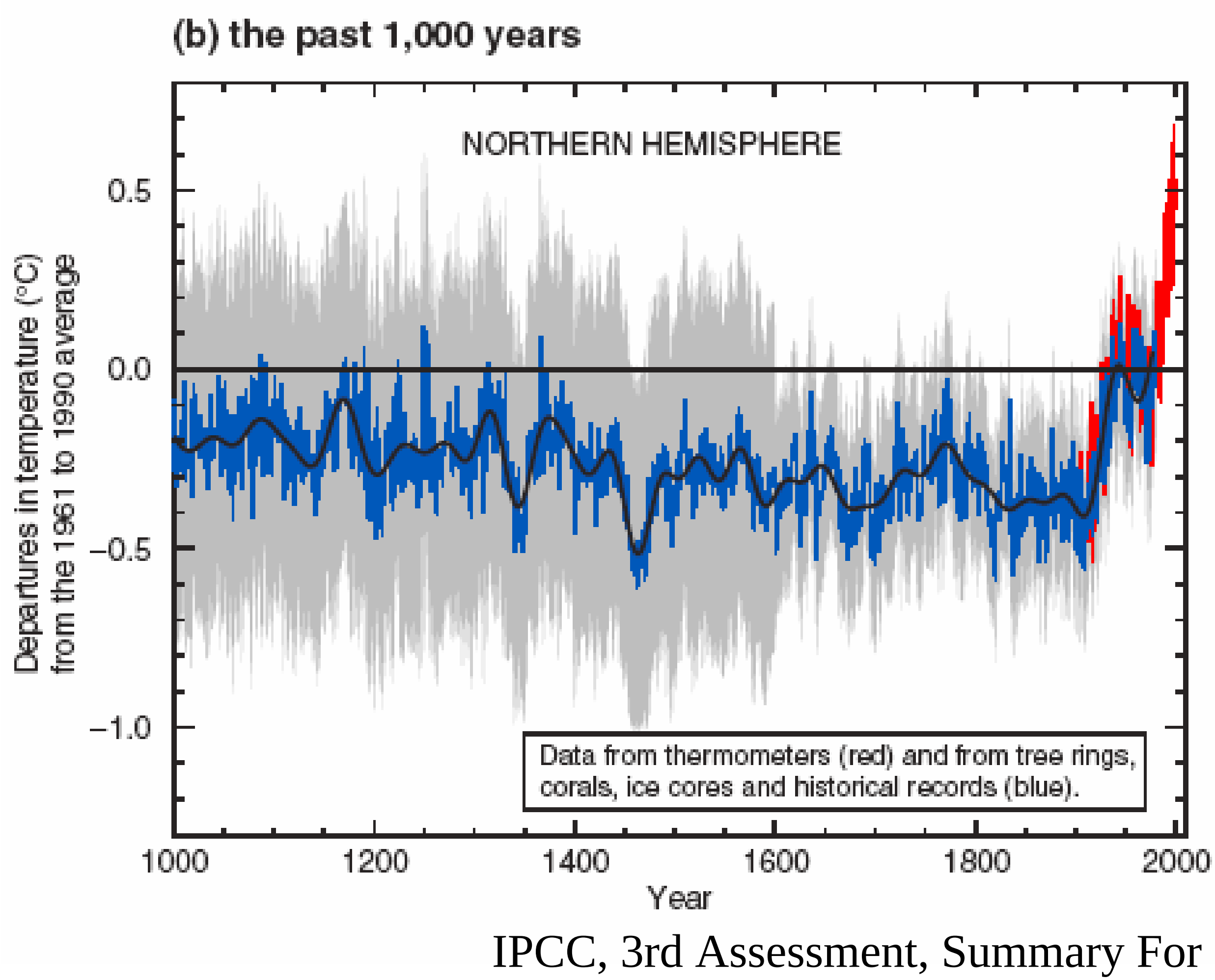
Observed Temperature Records



IPCC, 3rd Assessment, Summary For Policymakers

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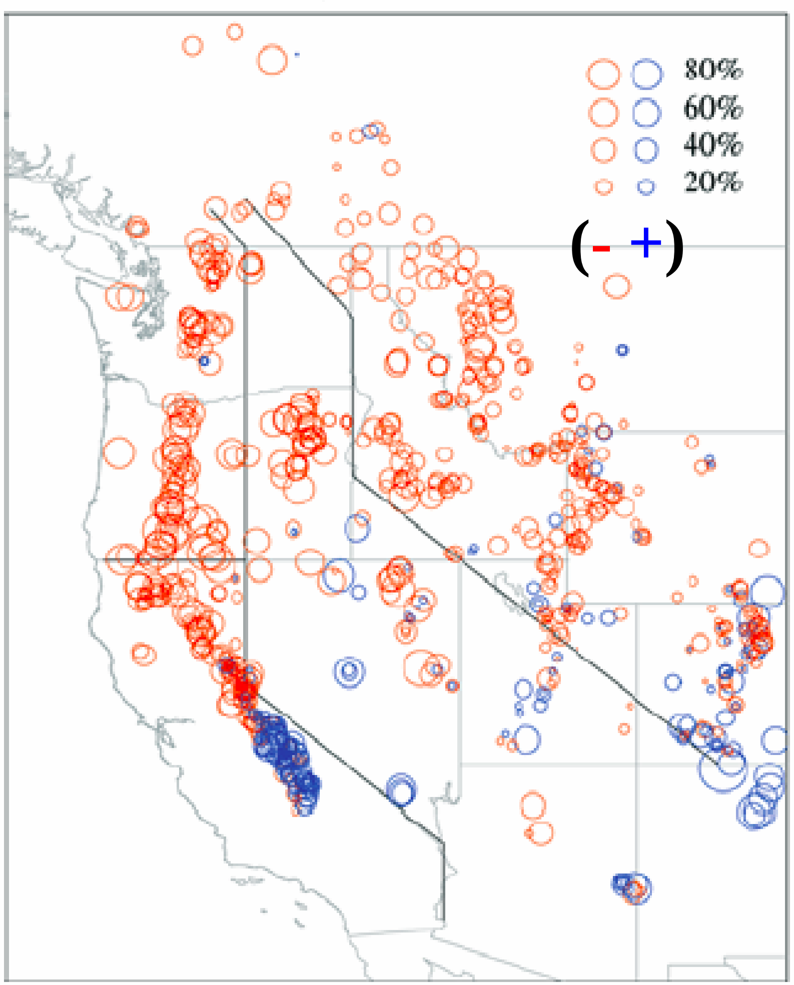
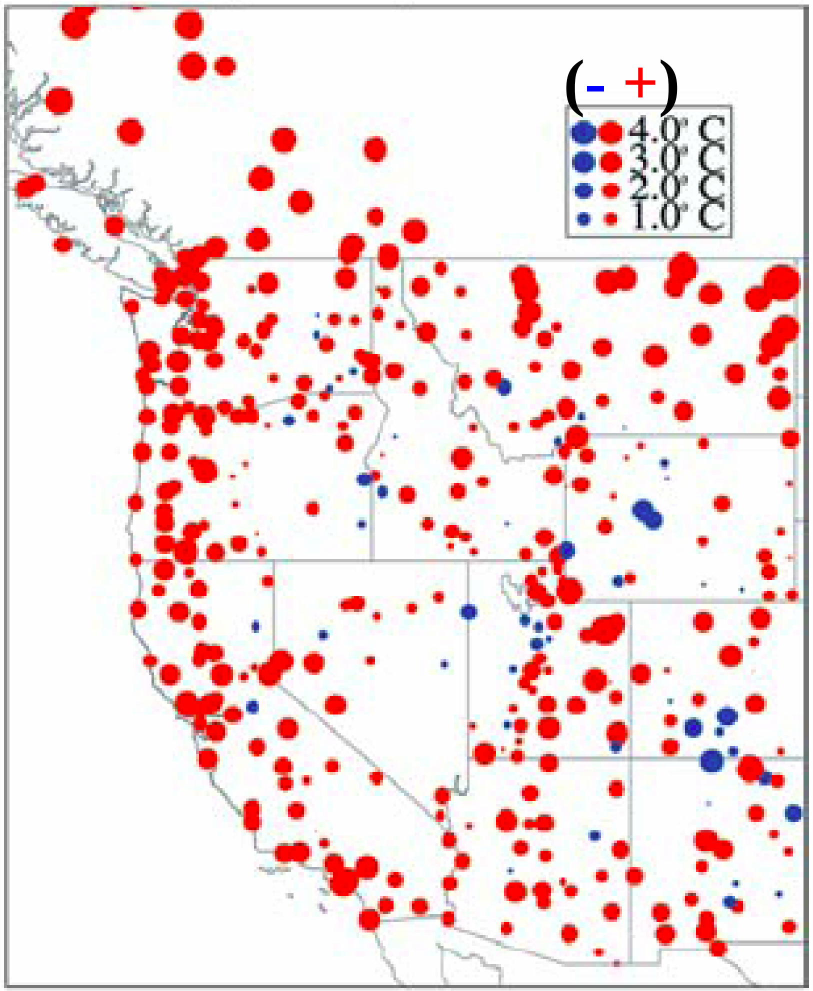
Impacts of Climate Change

Observed Change 1950-1997

Snowpack



Temperature



Mote et al 2005

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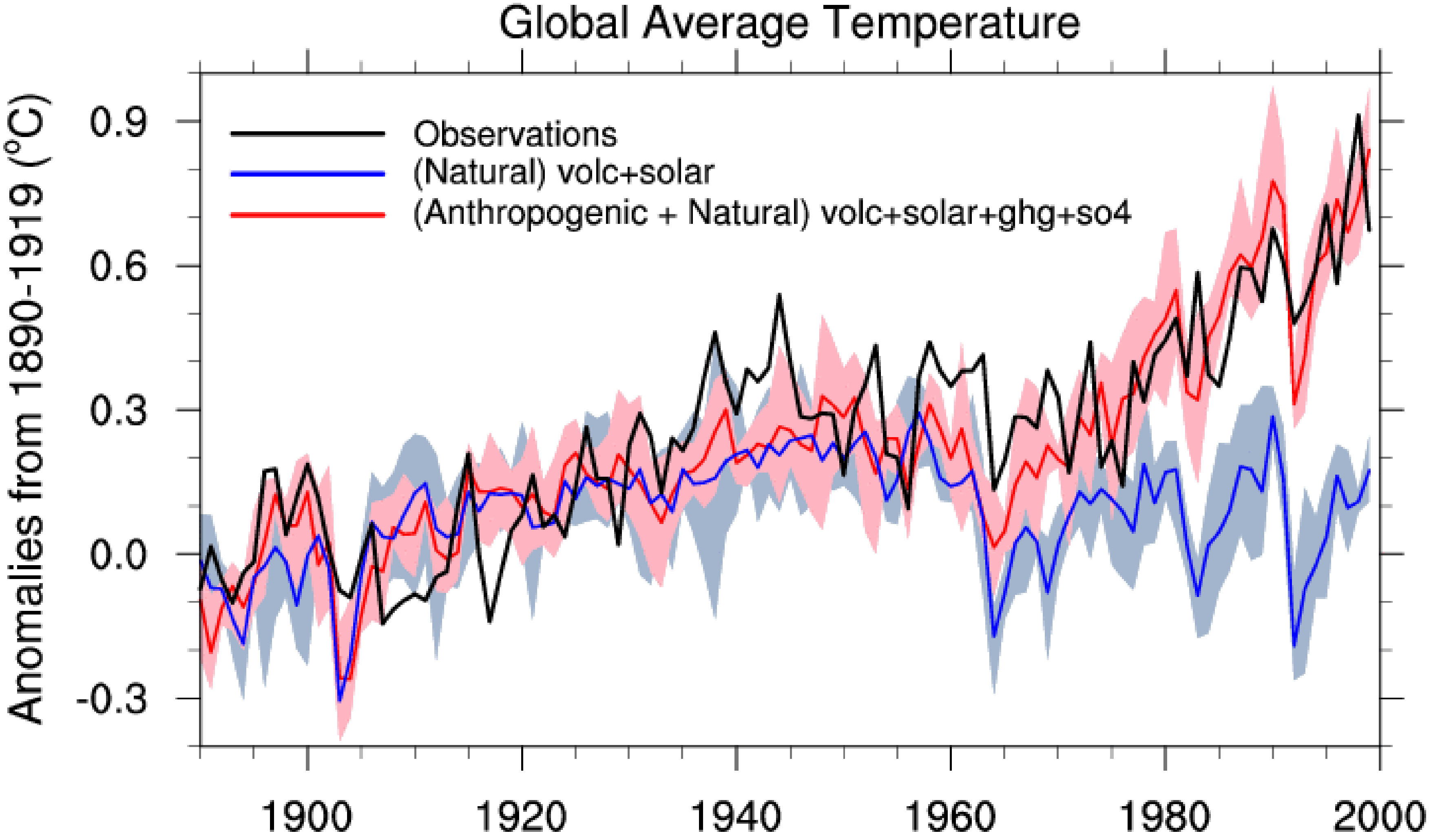
Observations: 20th Century Warming
Model Solutions with Human Forcing



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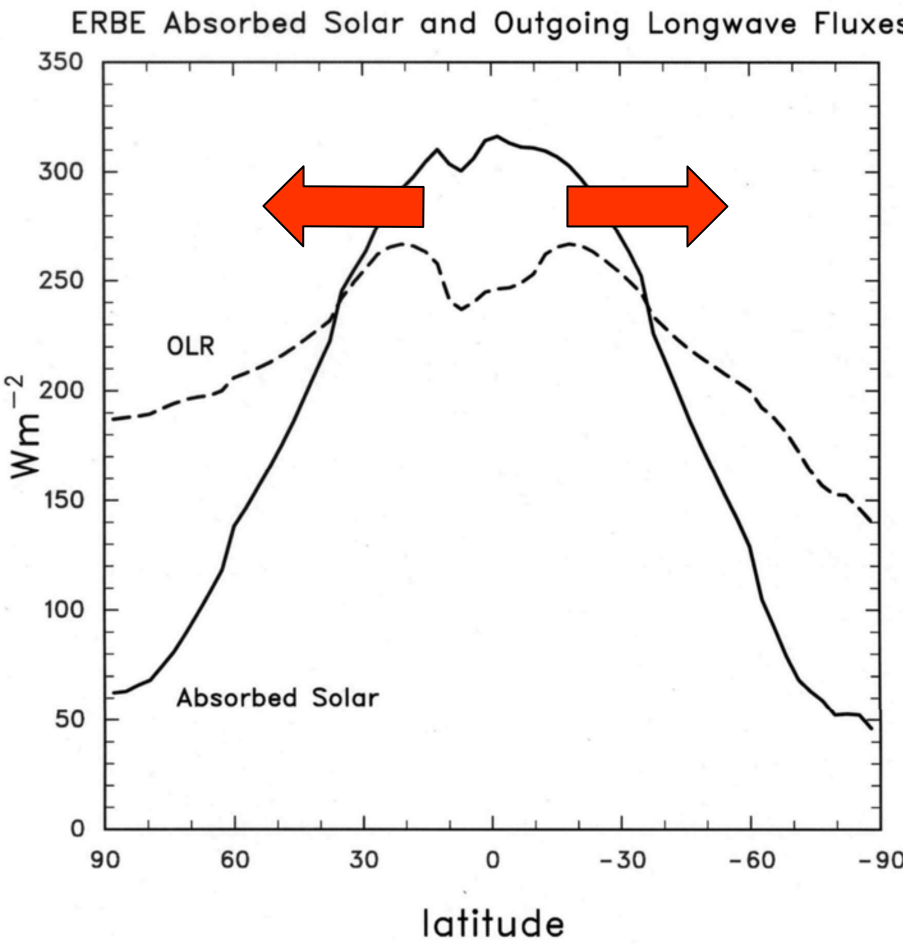
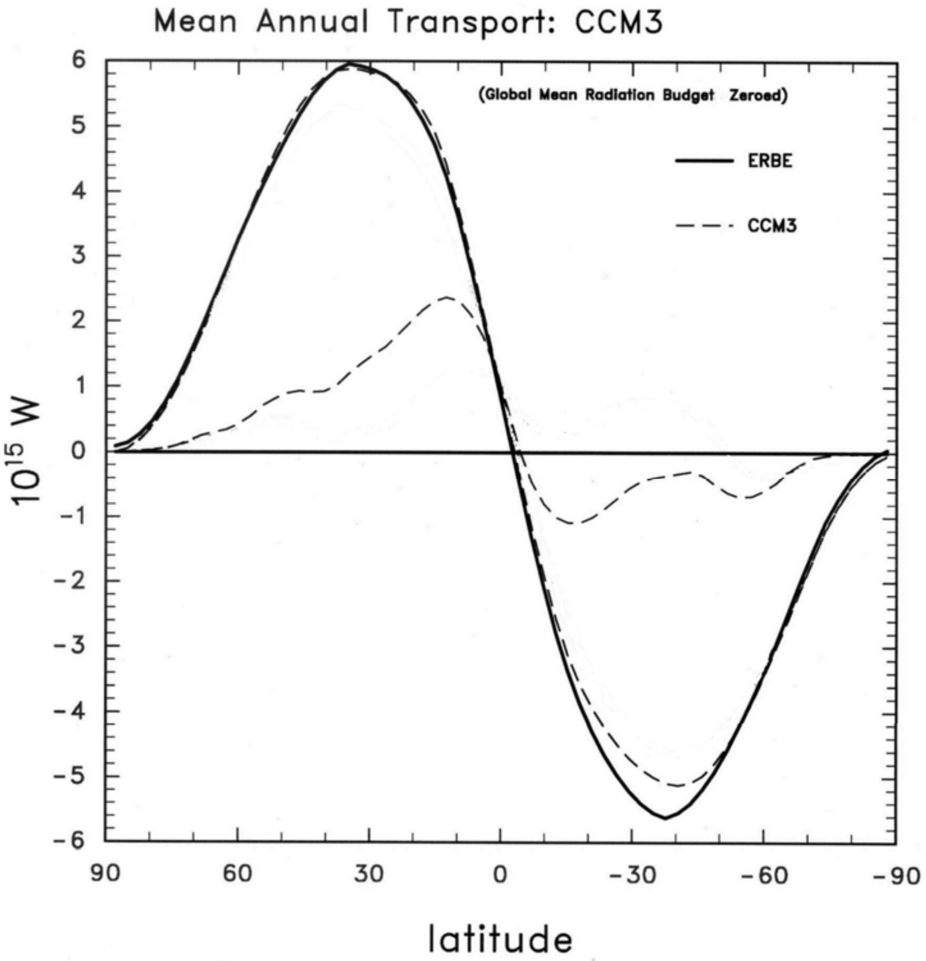
Energy Balance: Fundamental Driver of the Scientific Problem

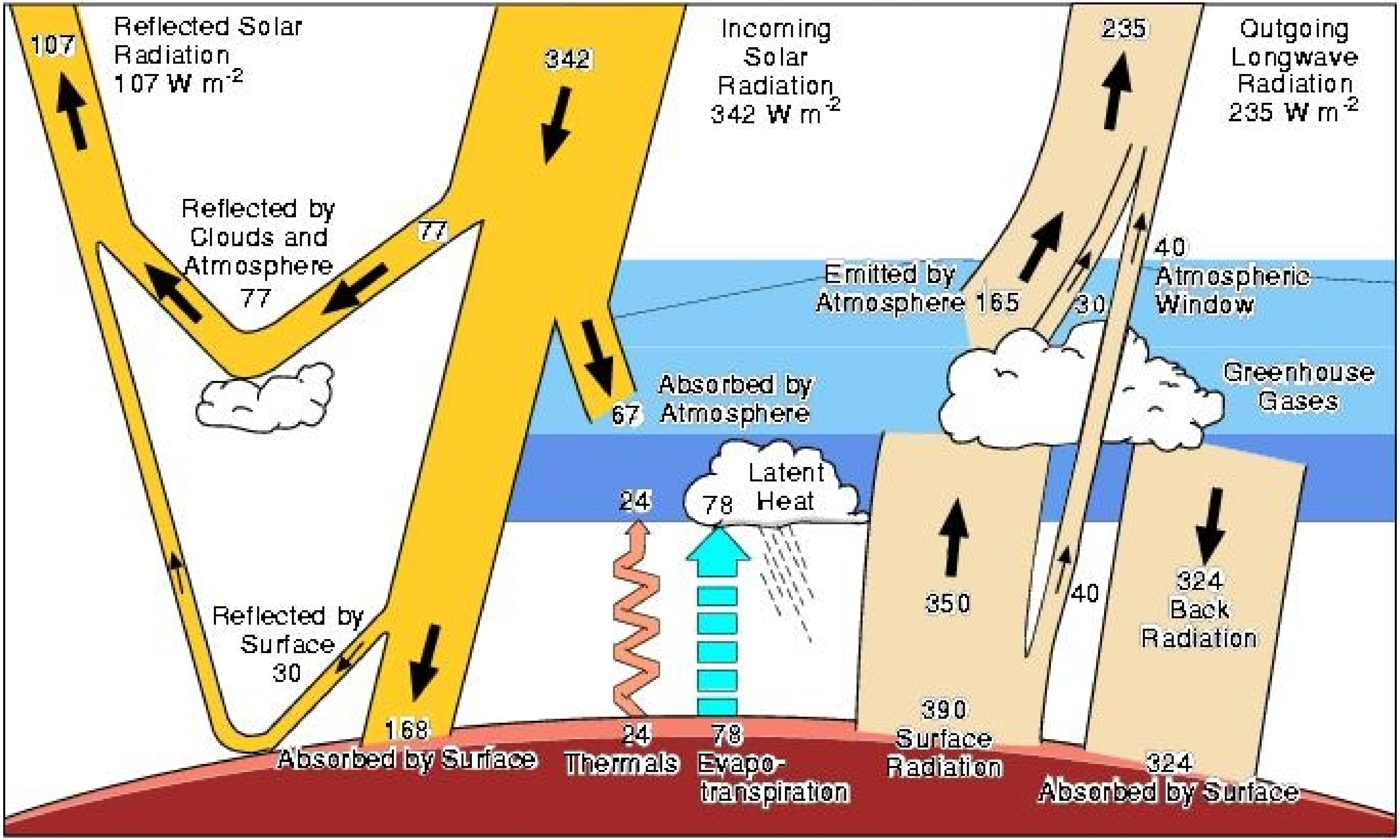
Longwave and Shortwave Energy Budget



Northward Energy Transport



Global Heat Flows



Kiehl and Trenberth 1997

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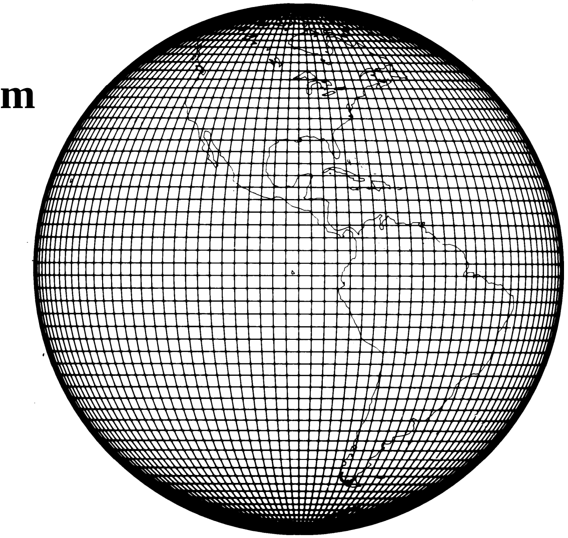
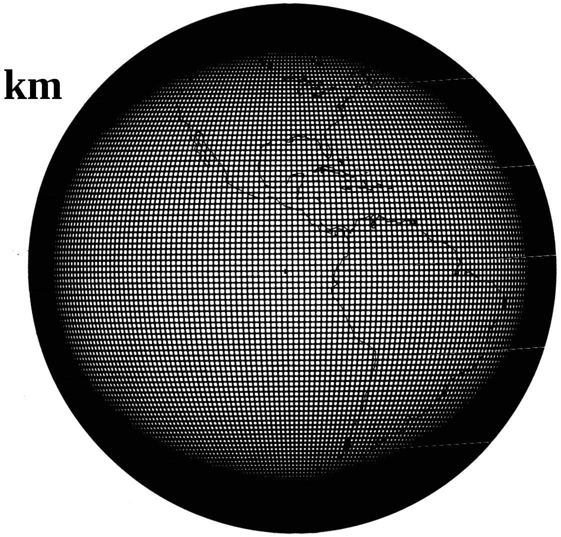
Computational Balancing Act

- Quality of solutions are resolution and physics limited
  - balance horizontal and vertical resolution, and physics complexity
  - *computational capability 0th-order rate limiter*

Δx = 300 km

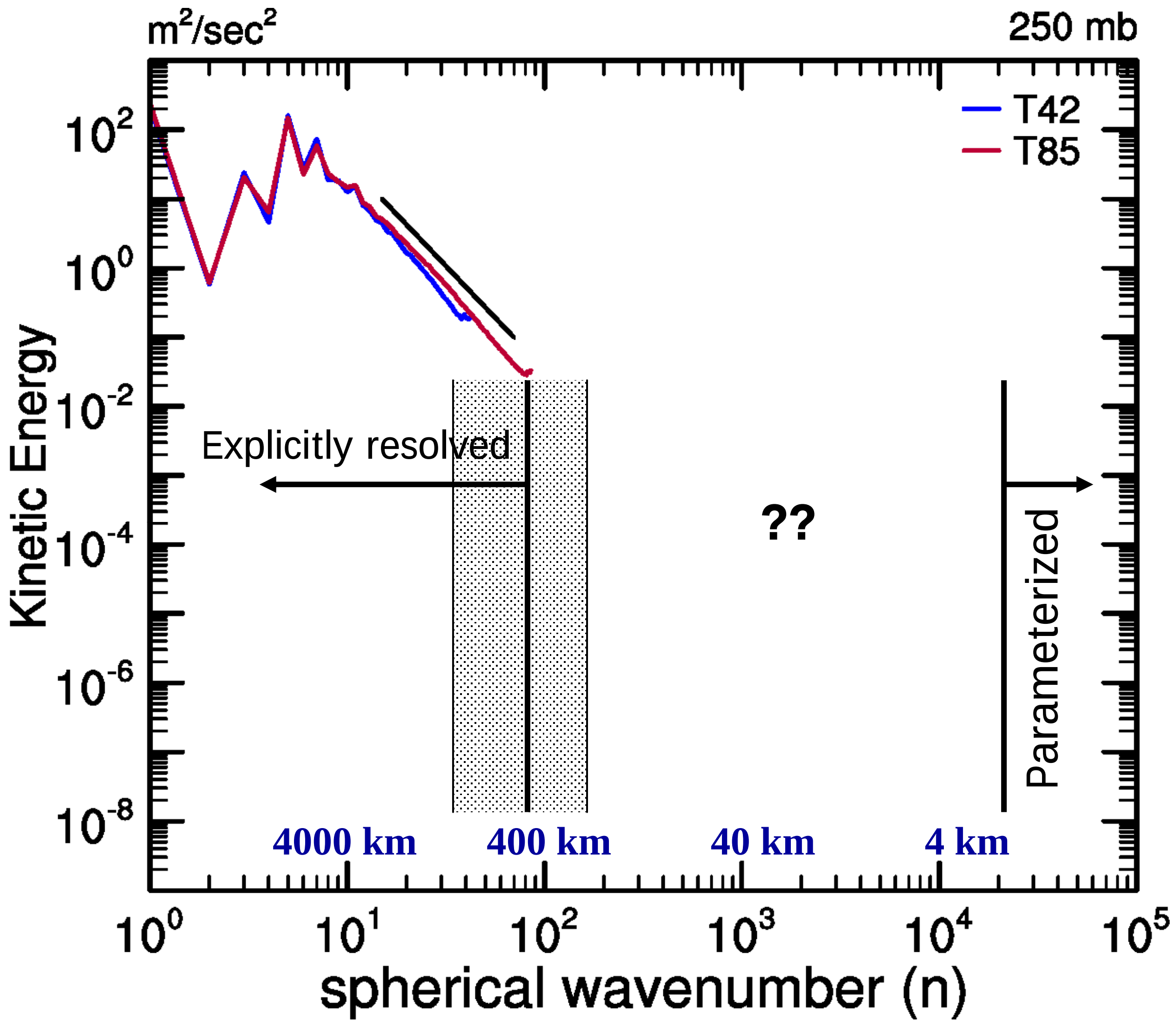


Δx = 150 km



- Long integration times/ensembles required for climate
  - non-deterministic problem with large natural variability
  - long equilibrium time scales for coupled systems
  - *computational capability 0th-order rate limiter*

Atmospheric Motion Scales and Parameterization



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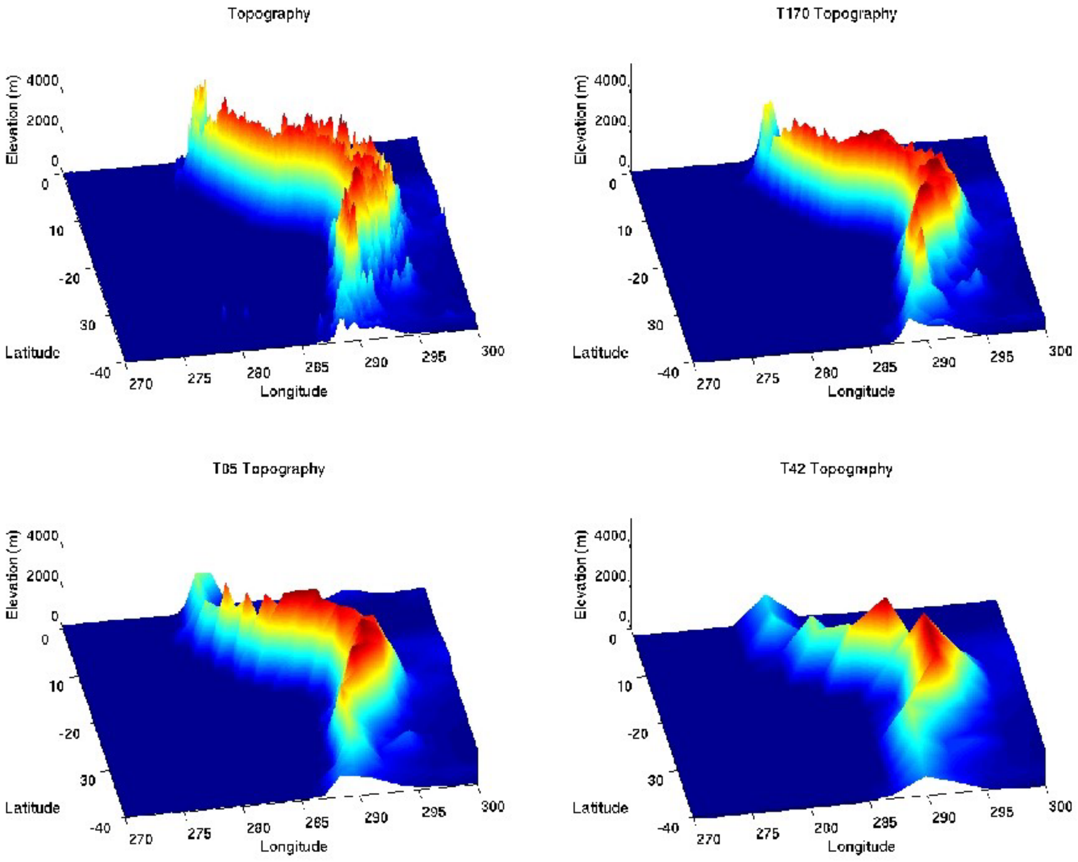
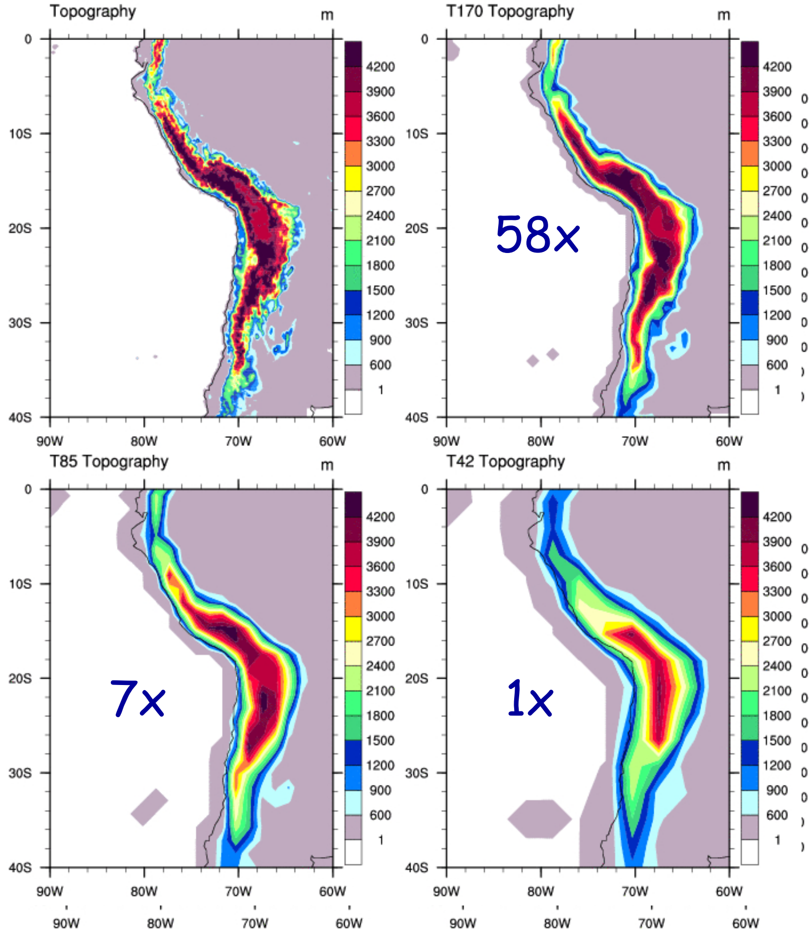
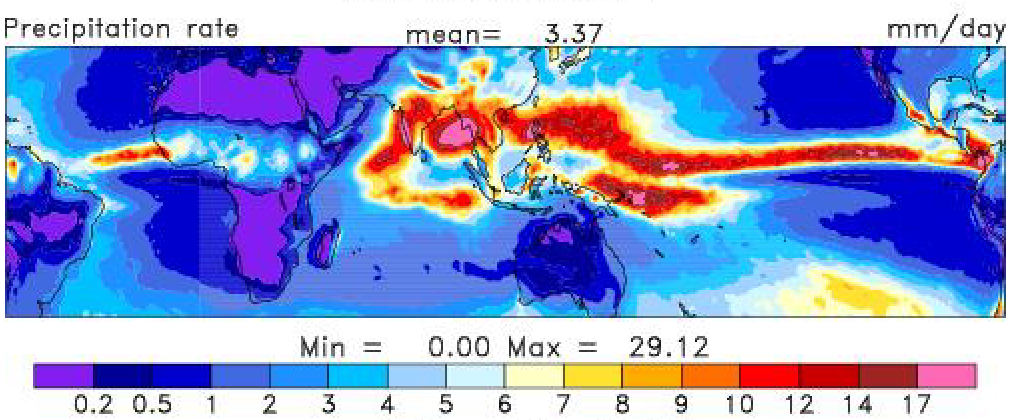
Global Modeling and Horizontal Resolution





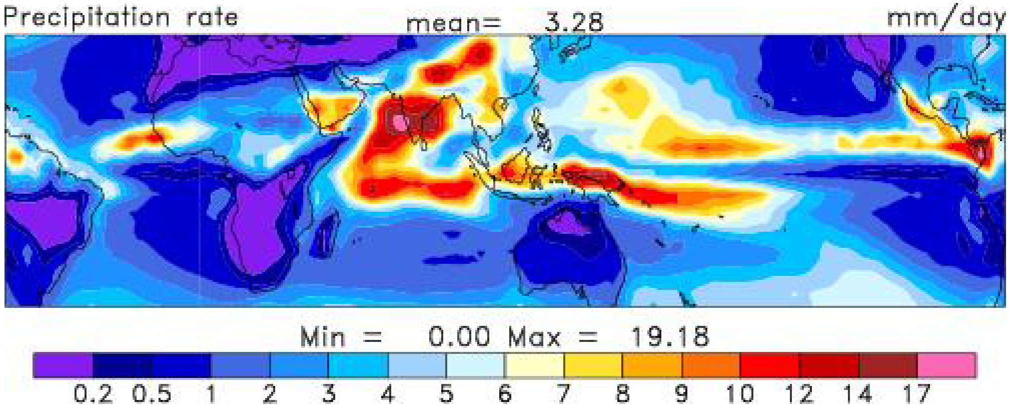
Simulation Improvements in Mean Measures

high-resolution



cam20shrconst (yrs 10-29)

standard



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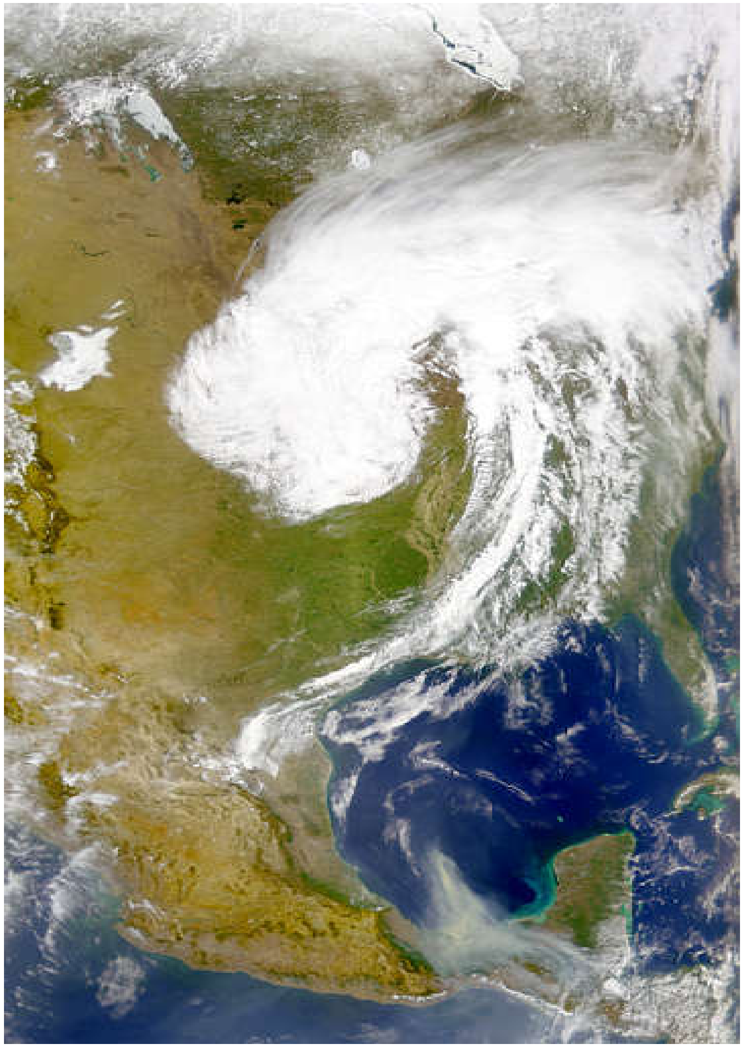
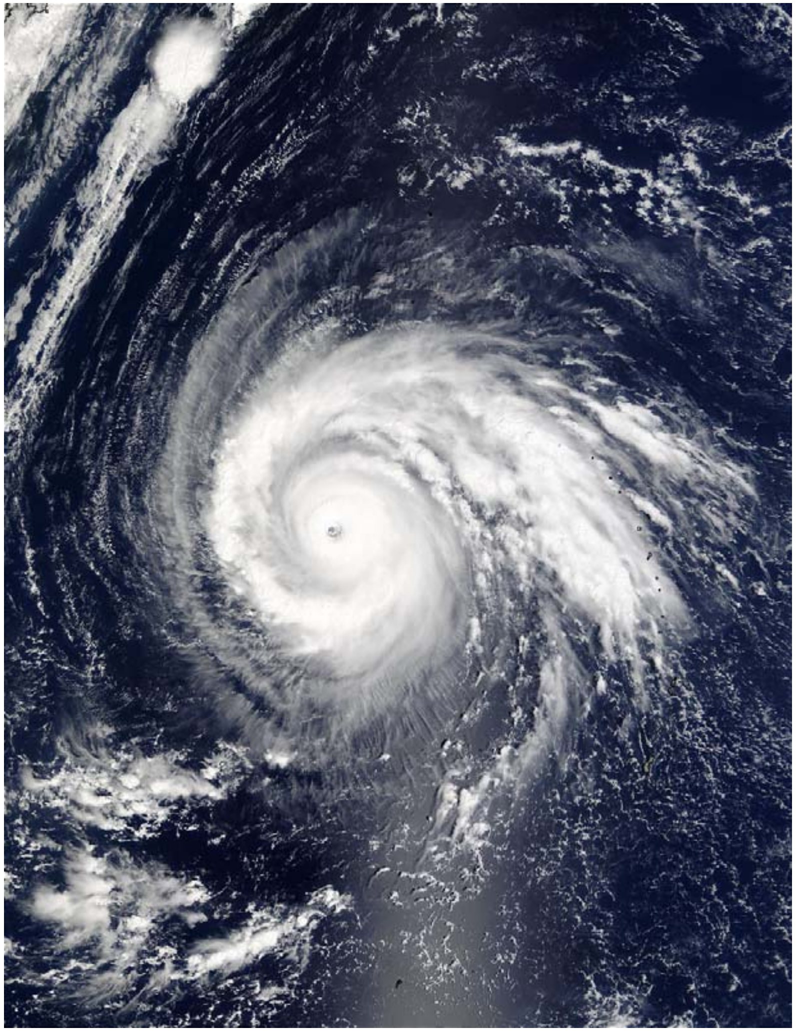
Atmospheric Energy Transport

Synoptic-scale mechanisms

- extratropical storms



- hurricanes



http://www.earth.nasa.gov

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Capturing Primary Phenomenological Scales of Motion in Global Models

Simulation of Tropical Cyclone Impacts on Climate

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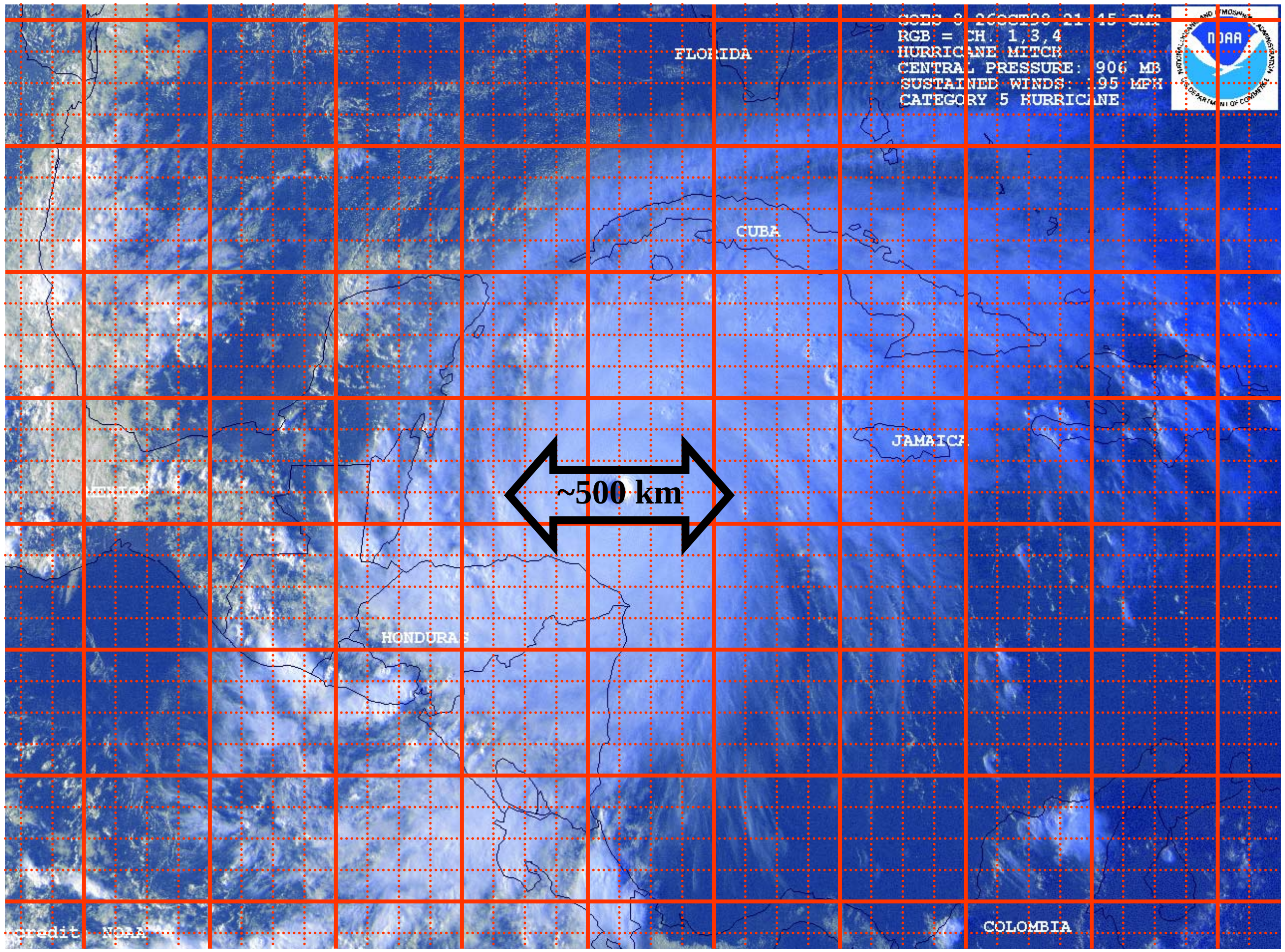
Courtesy, Raymond Zehr, NOAA CIRA

IMAGE TOY 31 October 2005

High-Resolution Global Modeling

Simulation of Tropical Cyclone Impacts on Climate



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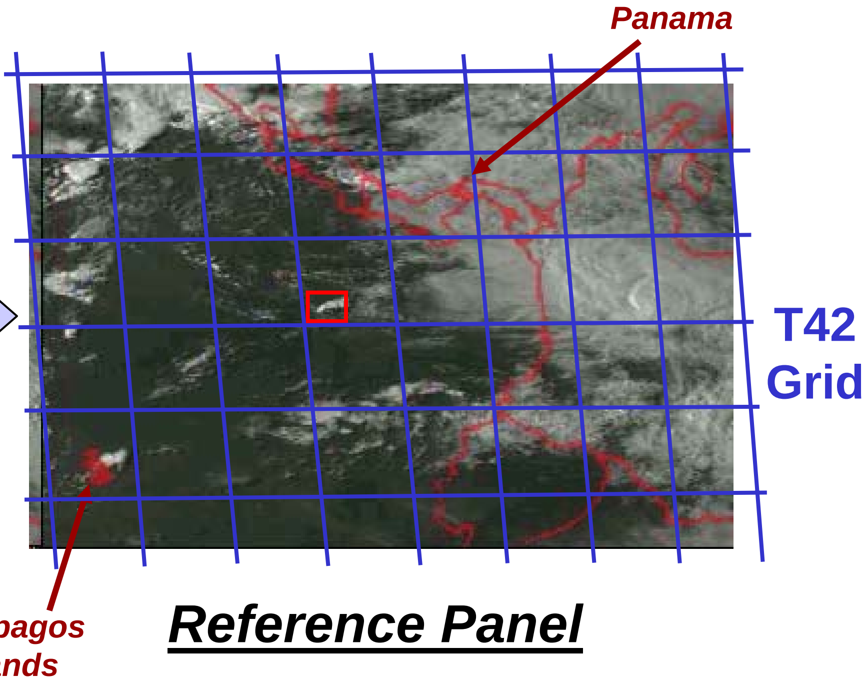
High-Resolution Global Modeling

Still a Need to Treat Subgrid-Scale Processes

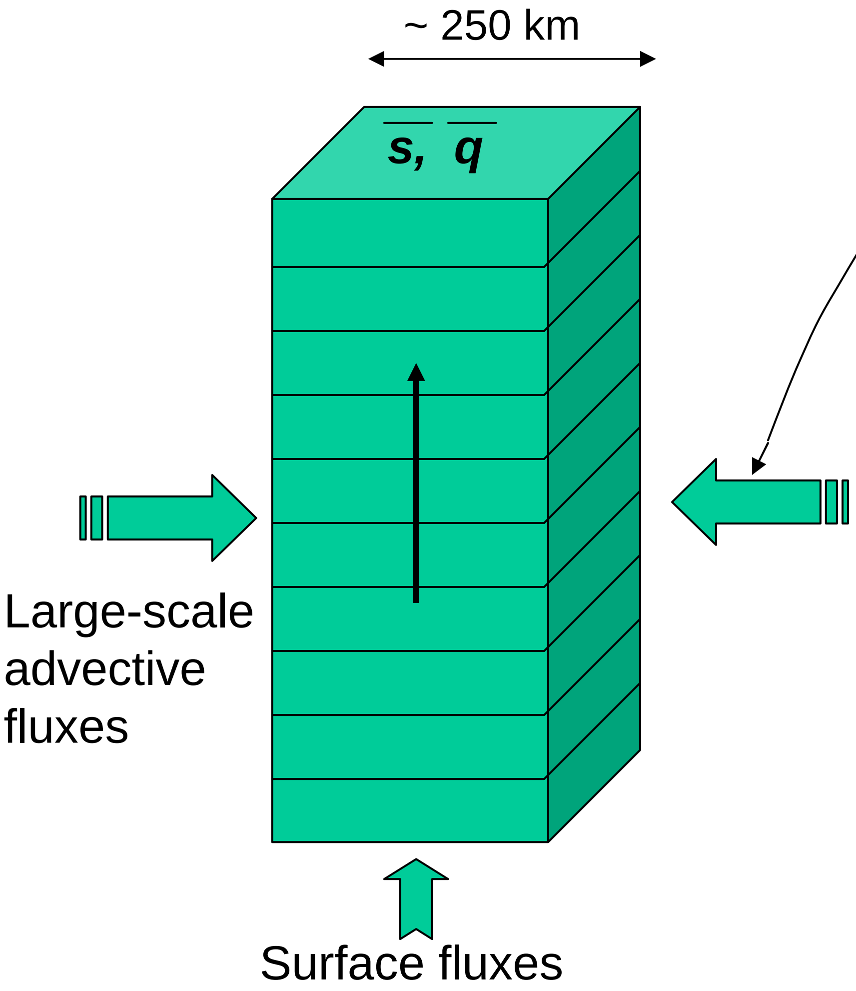
zoom



Reference Panel

Courtesy, NASA Goddard Space Flight Center Scientific Visualization Studio

The Cumulus Parameterization Problem



$$\boxed{\frac{\partial \bar{s}}{\partial t} = -\nabla\cdot\bar{\mathbf{V}}\bar{s} - \frac{\partial\bar{\omega}\bar{s}}{\partial p}} - \boxed{\frac{\partial}{\partial p}(\overline{\omega' s_l'}) + L\Re + c_p Q_R}$$

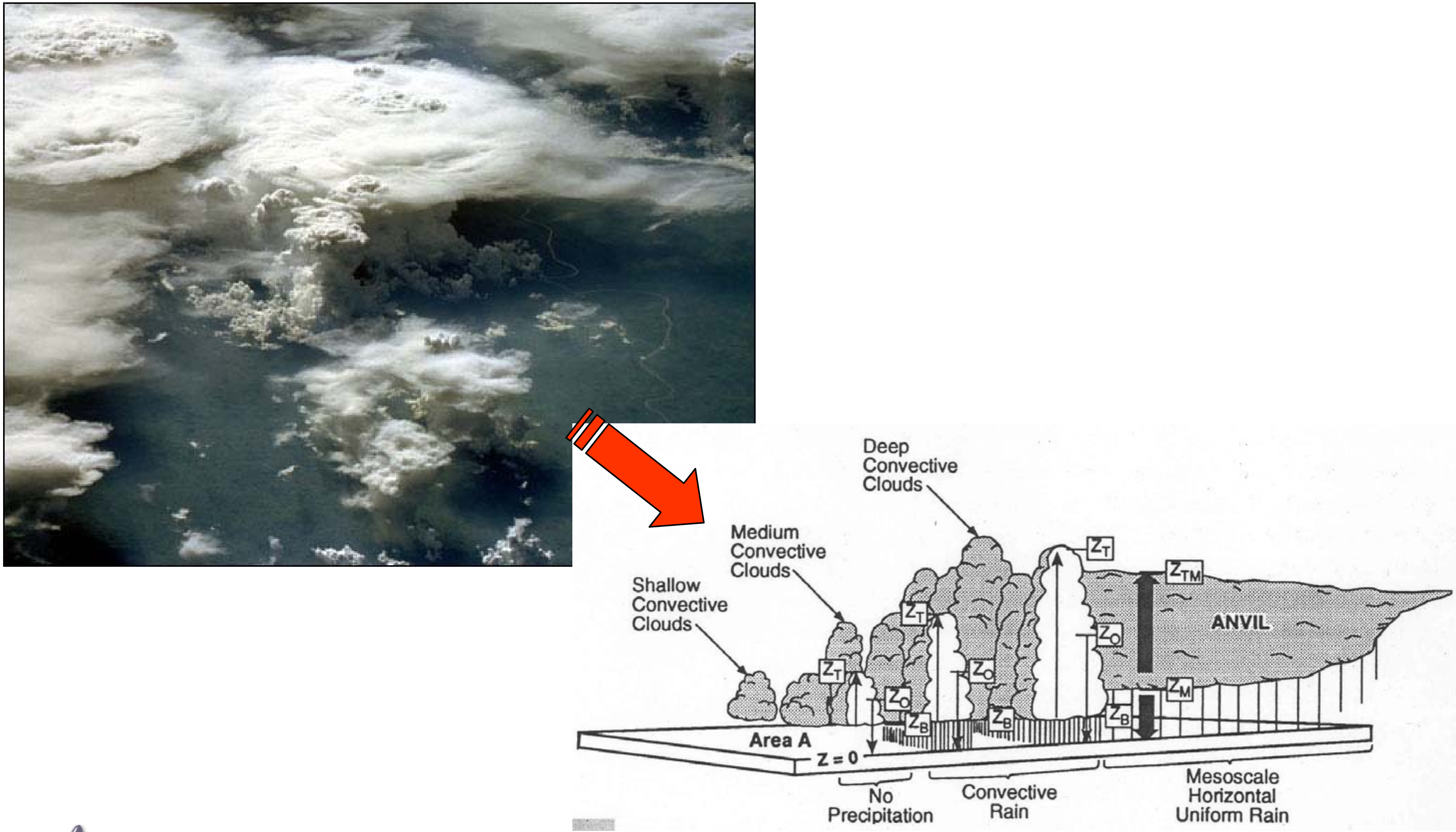
$$\boxed{\frac{\partial \bar{q}}{\partial t} = -\nabla\cdot\bar{\mathbf{V}}\bar{q} - \frac{\partial\bar{\omega}\bar{q}}{\partial p}} - \boxed{\frac{\partial}{\partial p}(\overline{\omega'(q'+l')}) - \Re}$$

we resolve the "large scale"

and parameterize the unresolved scales

Can be treated/investigated in a single column framework

Process Models and Parameterization



Does Resolution Matter at the Process Level?

Moist Convection Example

Heat
$$\frac{\partial \bar{s}}{\partial t} = \boxed{-\nabla\cdot\bar{\mathbf{V}}\bar{s} - \frac{\partial \bar{\omega}\bar{s}}{\partial p}} - \boxed{\frac{\partial}{\partial p}\left(\overline{\omega' s_l'}\right) + L\Re + c_p Q_R}$$

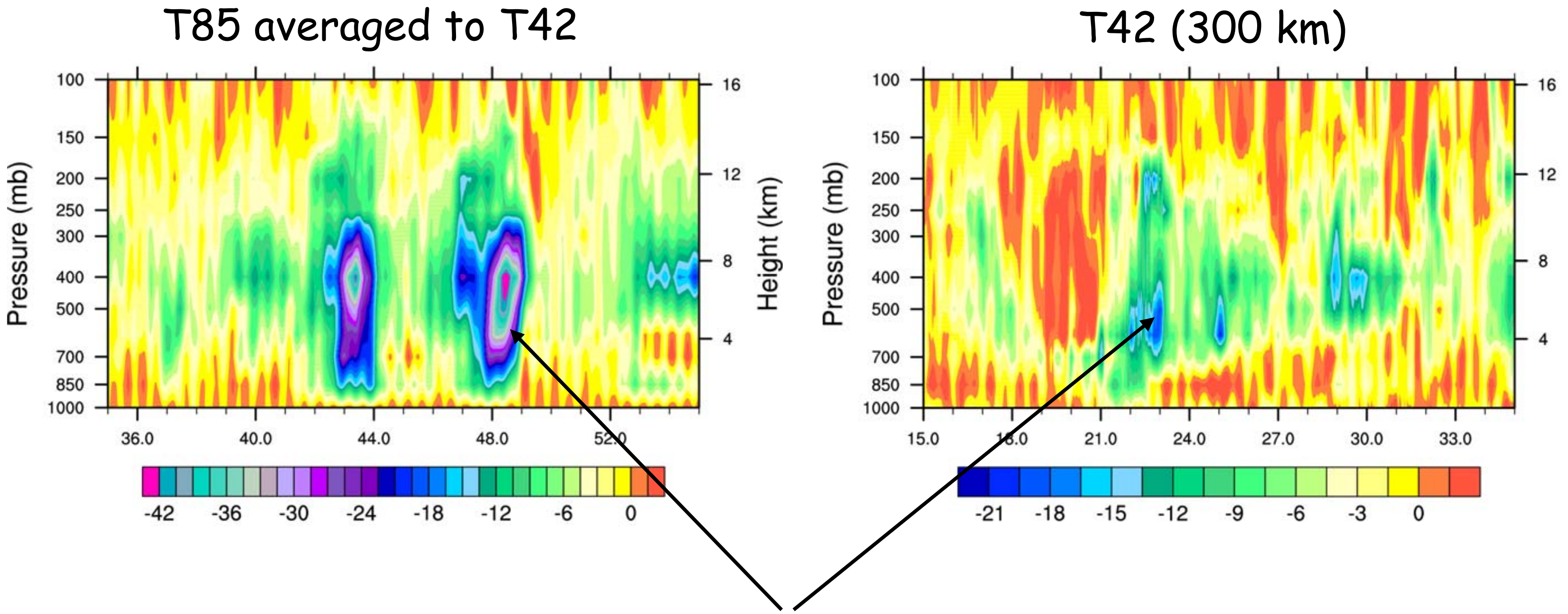
Moisture
$$\frac{\partial \bar{q}}{\partial t} = \boxed{-\nabla\cdot\bar{\mathbf{V}}\bar{q} - \frac{\partial \bar{\omega}\bar{q}}{\partial p}} - \boxed{\frac{\partial}{\partial p}\left(\overline{\omega'(q'+l')}\right) - \Re}$$

we resolve the
“large scale”

and parameterize the
unresolved scales

What happens to the “large-scale” motions seen by the parameterized physics as resolution is changed?

Warm Pool Temperature Forcing Time Series



Fundamentally different “large-scale” forcing of parameterized physics

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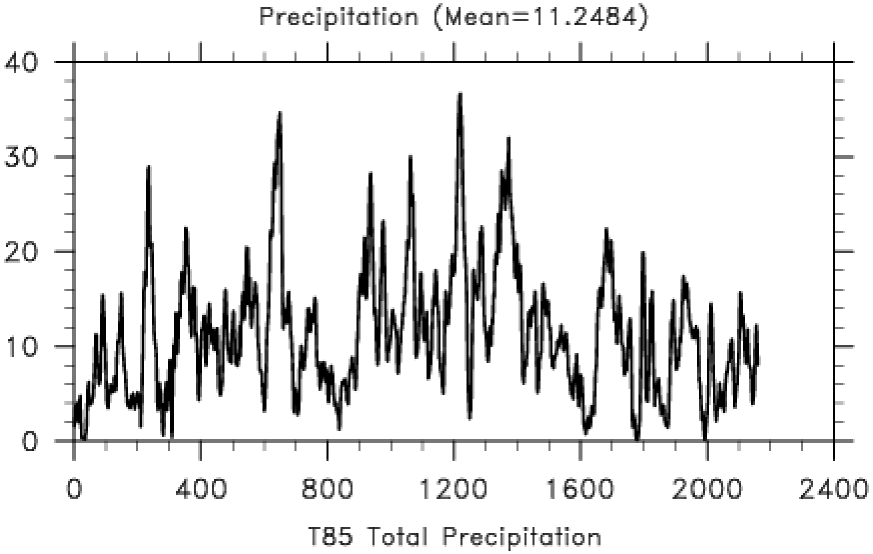
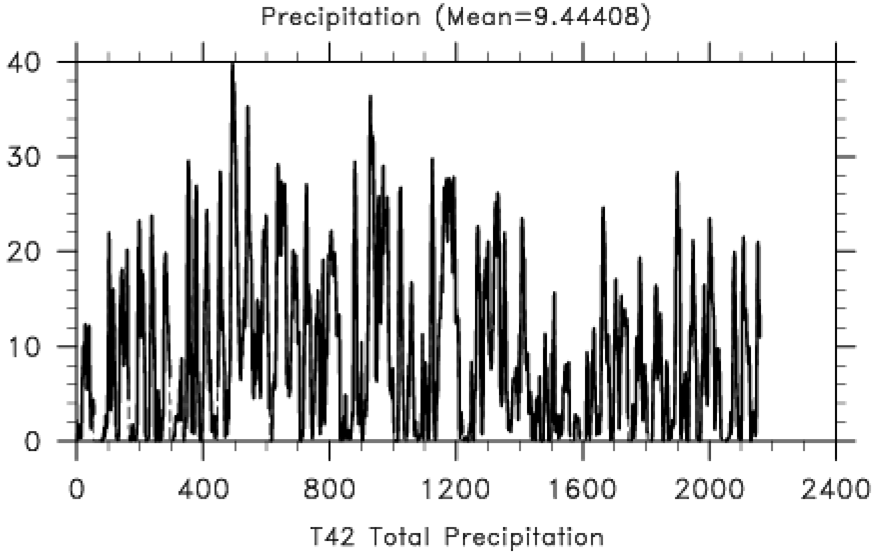
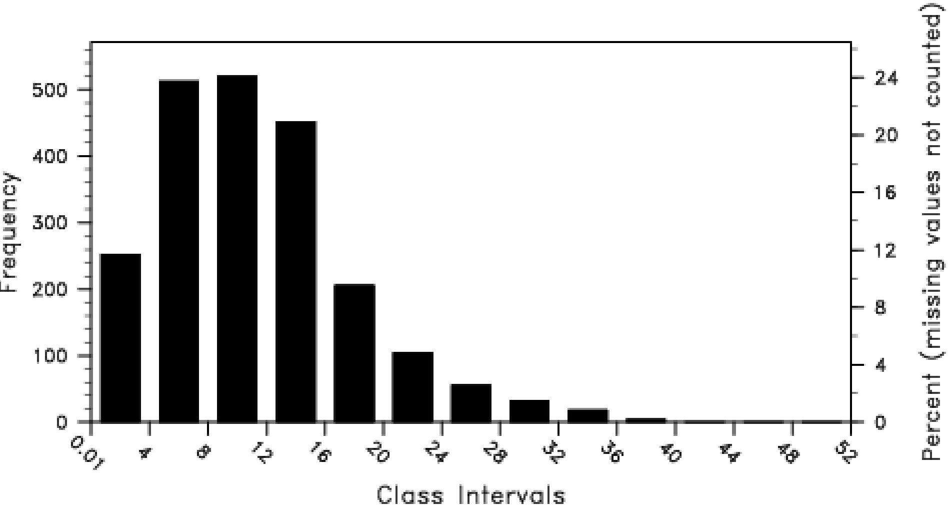
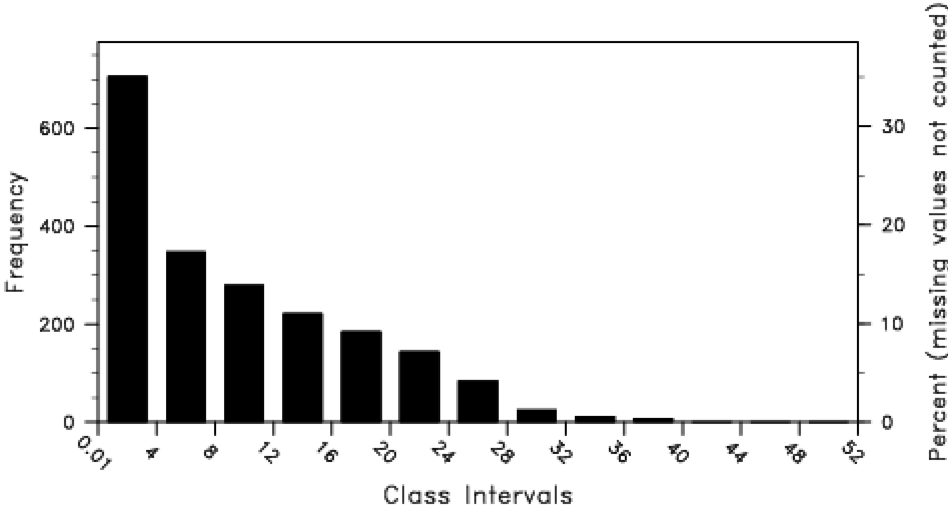
Warm Pool Precipitation Characteristics









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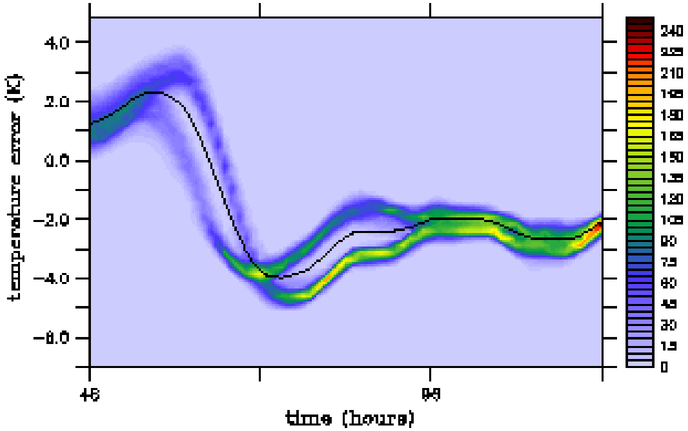
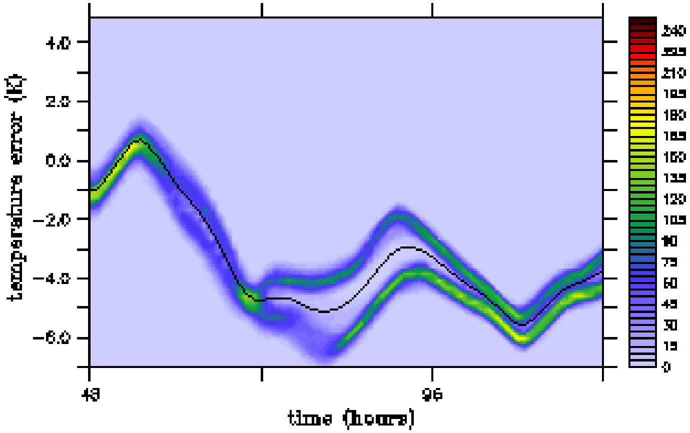
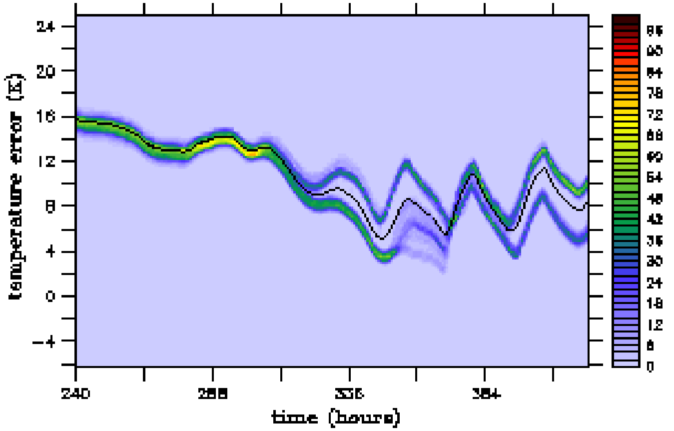
Nonlinearities in parameterized physics



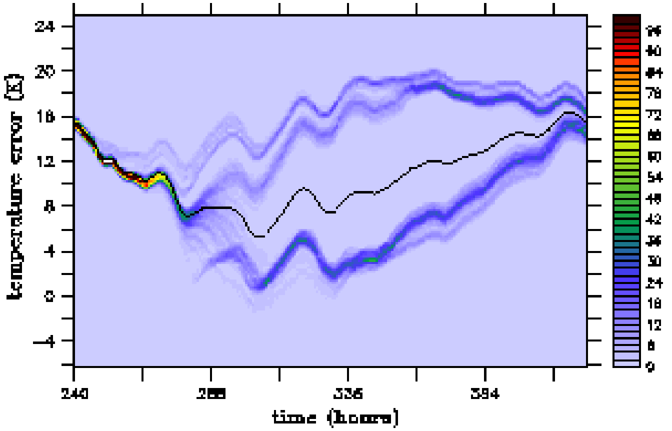
GCSS 873 mb Temperature Error



GCSS 701 mb Temperature Error



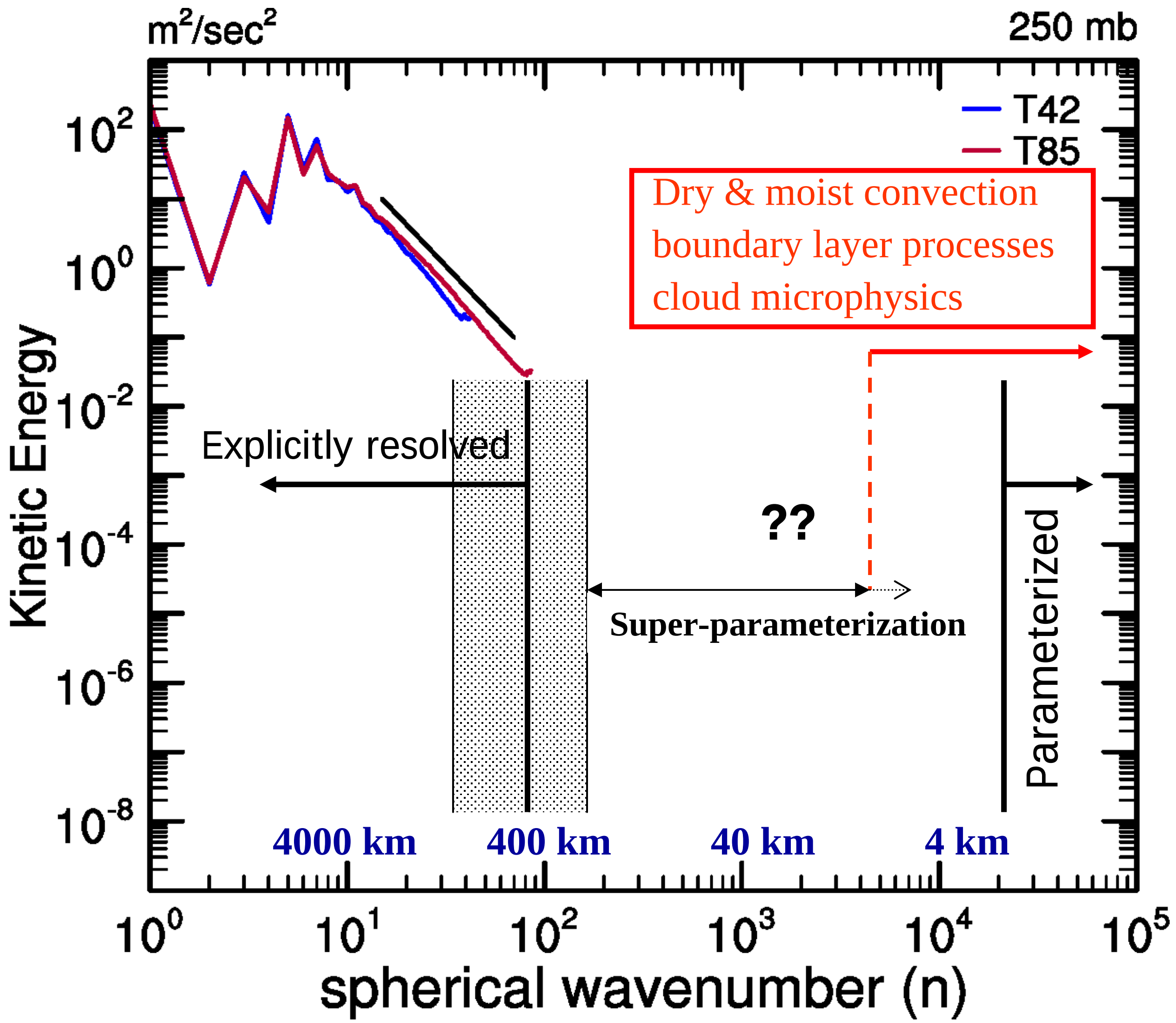
ARM 247 mb Temperature Error



ARM 909 mb Temperature Error

Hack and Pedretti (2000)

Atmospheric Motion Scales and Parameterization



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We cannot escape the parameterization problem

- Climate Sensitivity: the final frontier
  - what is the real climate sensitivity?
  - clearly linked to treatment of parameterized physics
    - *Clouds**!!***
  - may be linked to extensions to physical climate system
    - Chemistry!
    - *Carbon**!!***

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Parameterization of Clouds

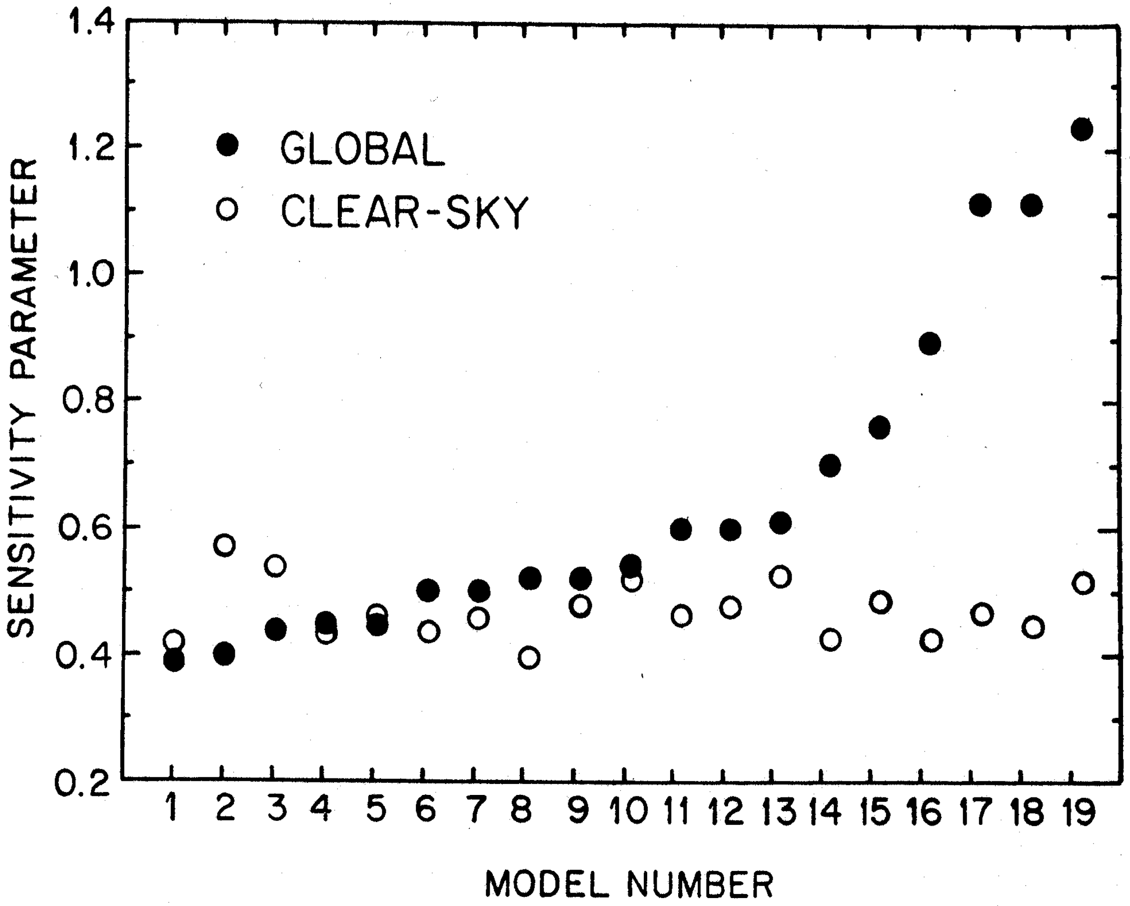

Fig. 1. Clear-sky and global sensitivity parameters (K m^2 W^{-1}) for the 19 GCMs. The model numbers correspond to the ordering in Table 9.

Cess et al. (1990)

Marine Stratus: Low Clouds over the Ocean

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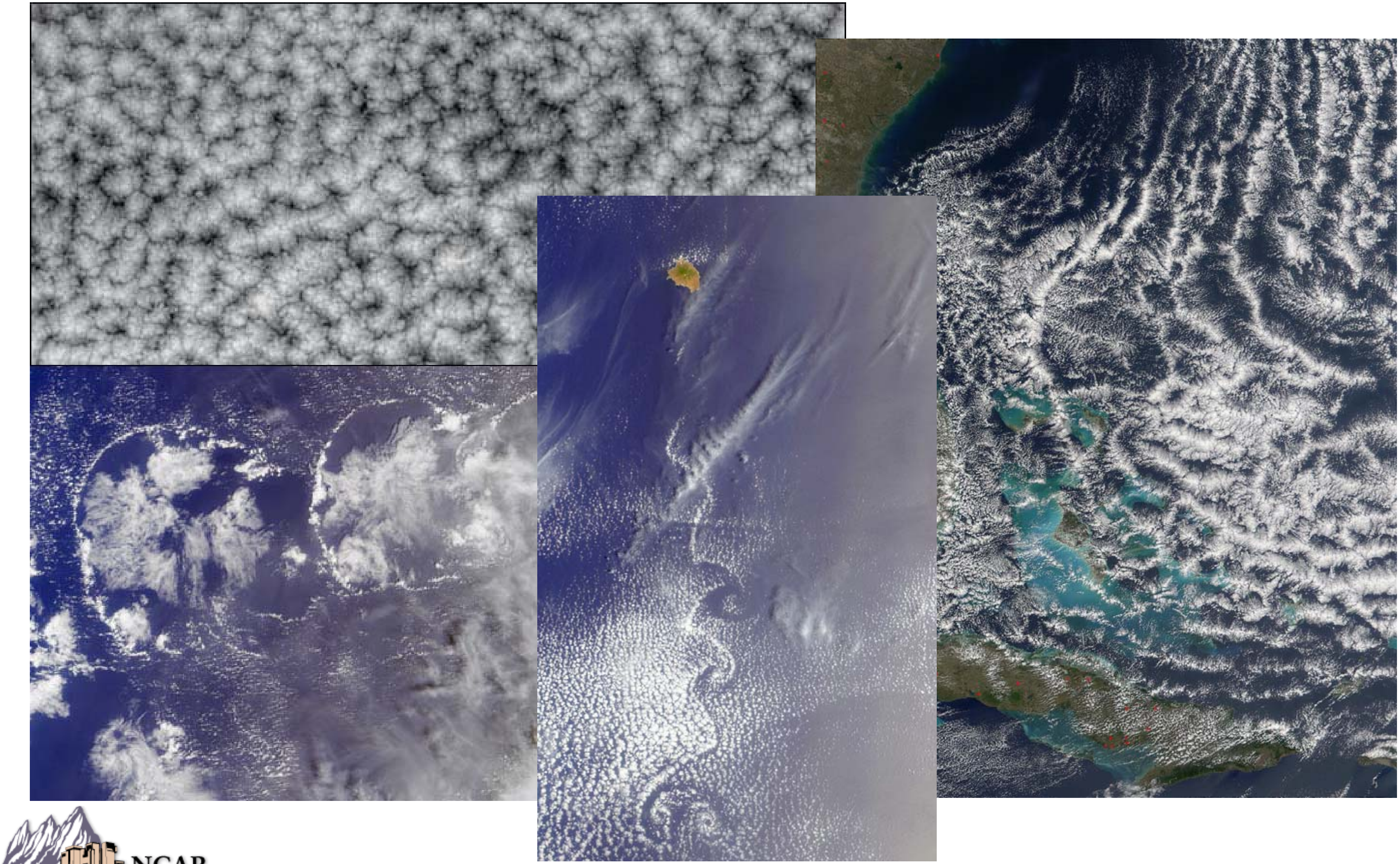
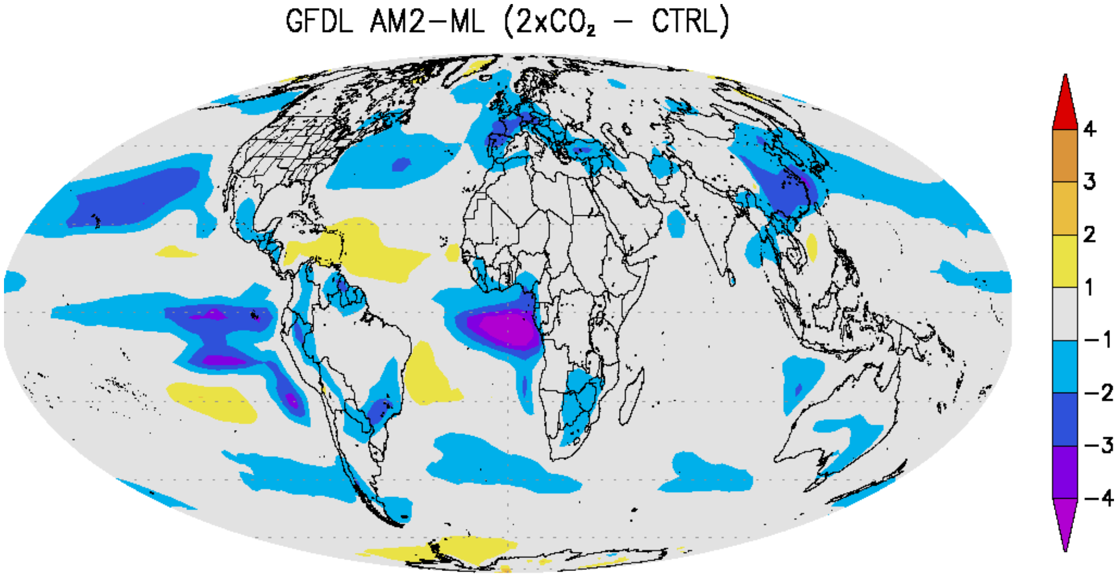
Other Energy Budget Impacts From Clouds



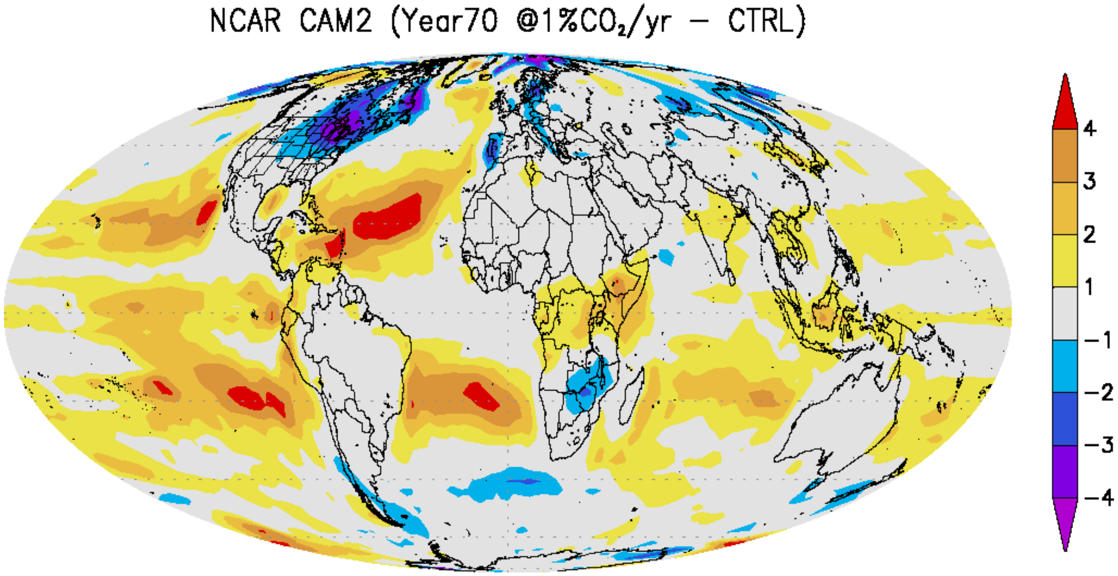
http://www.earth.nasa.gov

Low Clouds Over the Ocean

Two Models: Changes are OPPOSITE!



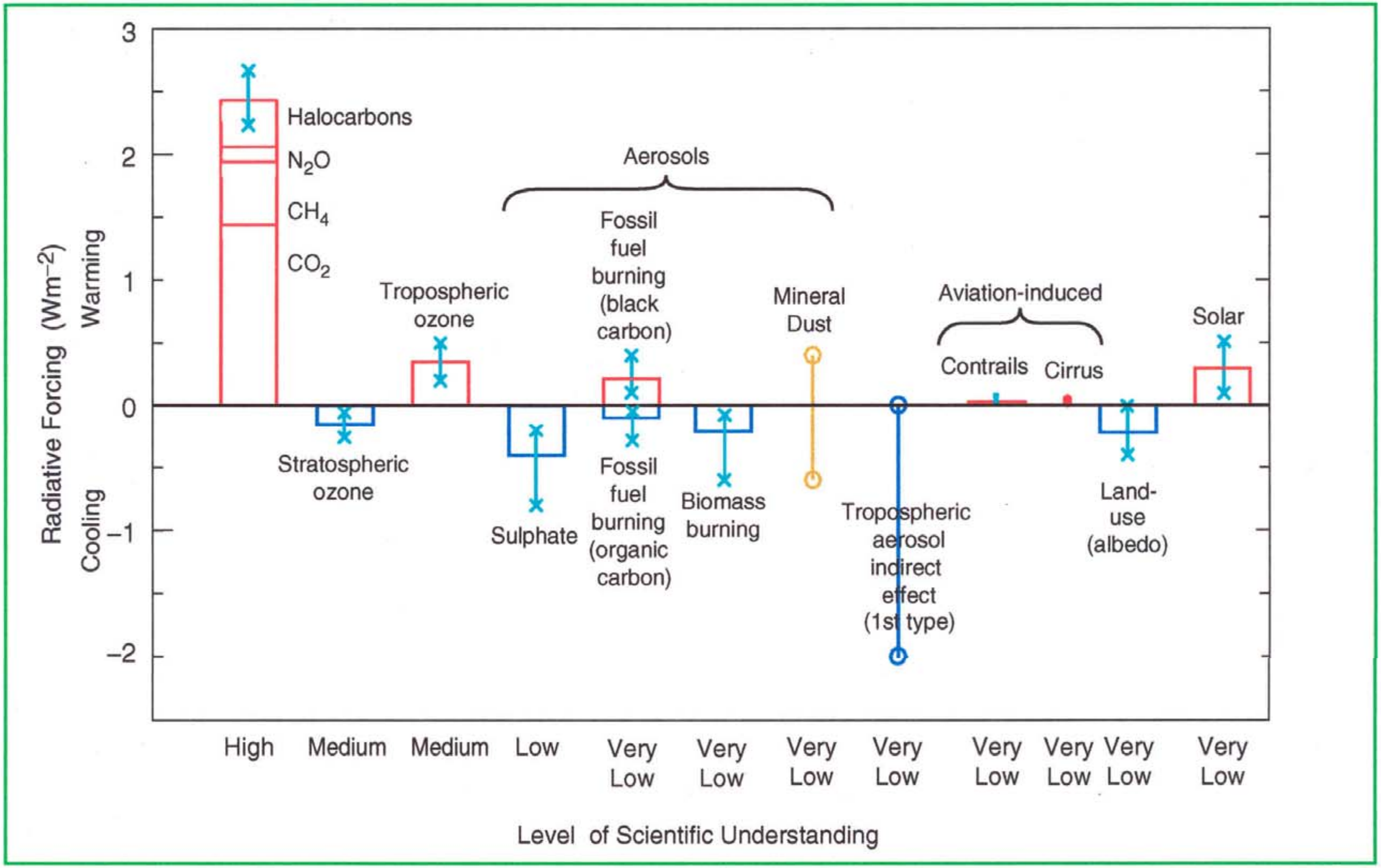
GFDL AM2–ML ($2\times CO_2$ – CTRL)



NCAR CAM2 (Year70 @1%CO_2/yr – CTRL)

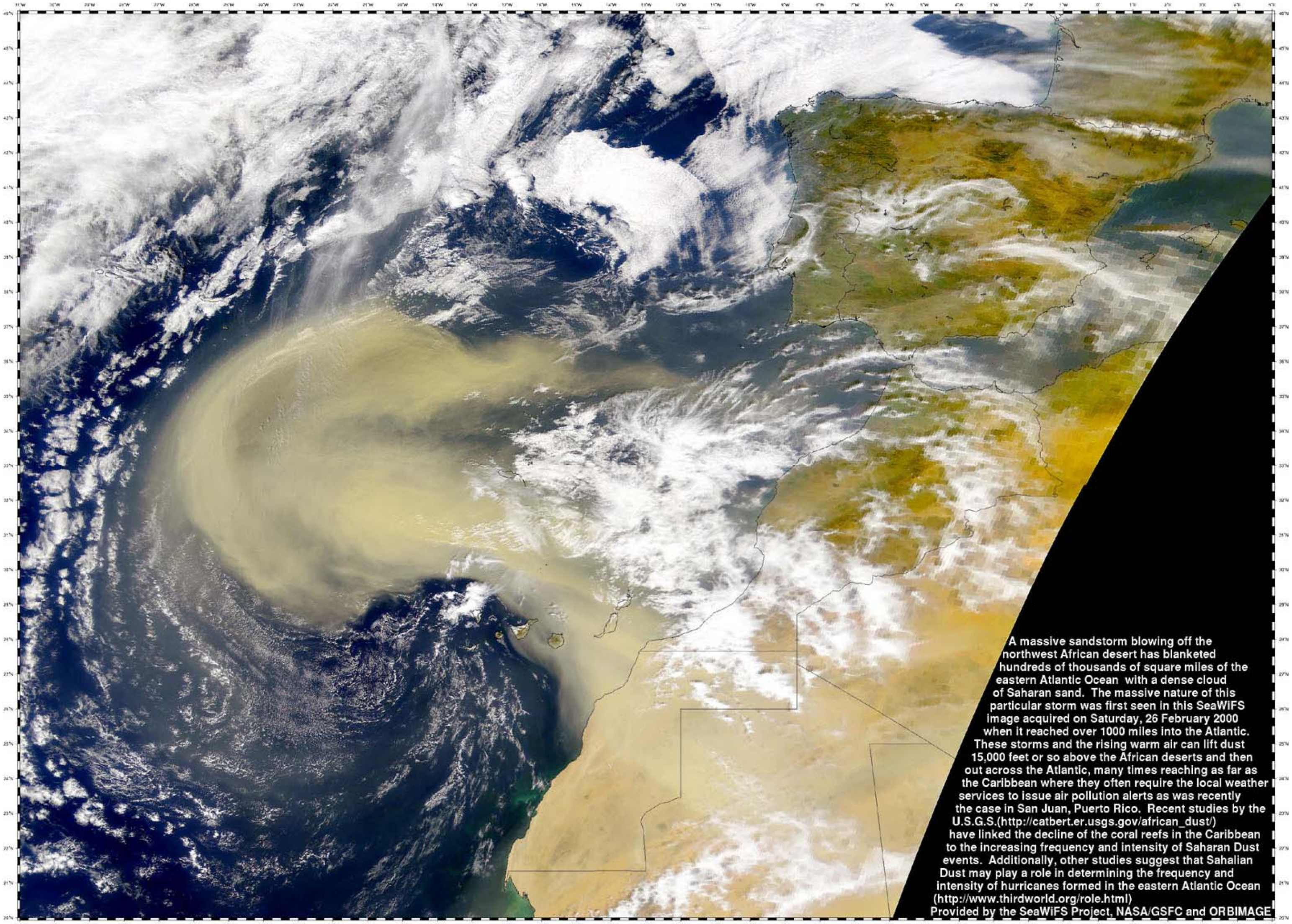
Change in Low Cloud Amount (%/K)

Some Other Sources of Uncertainty



IPCC Working Group I (2001)

Energy Budget Impacts of Atmospheric Aerosol

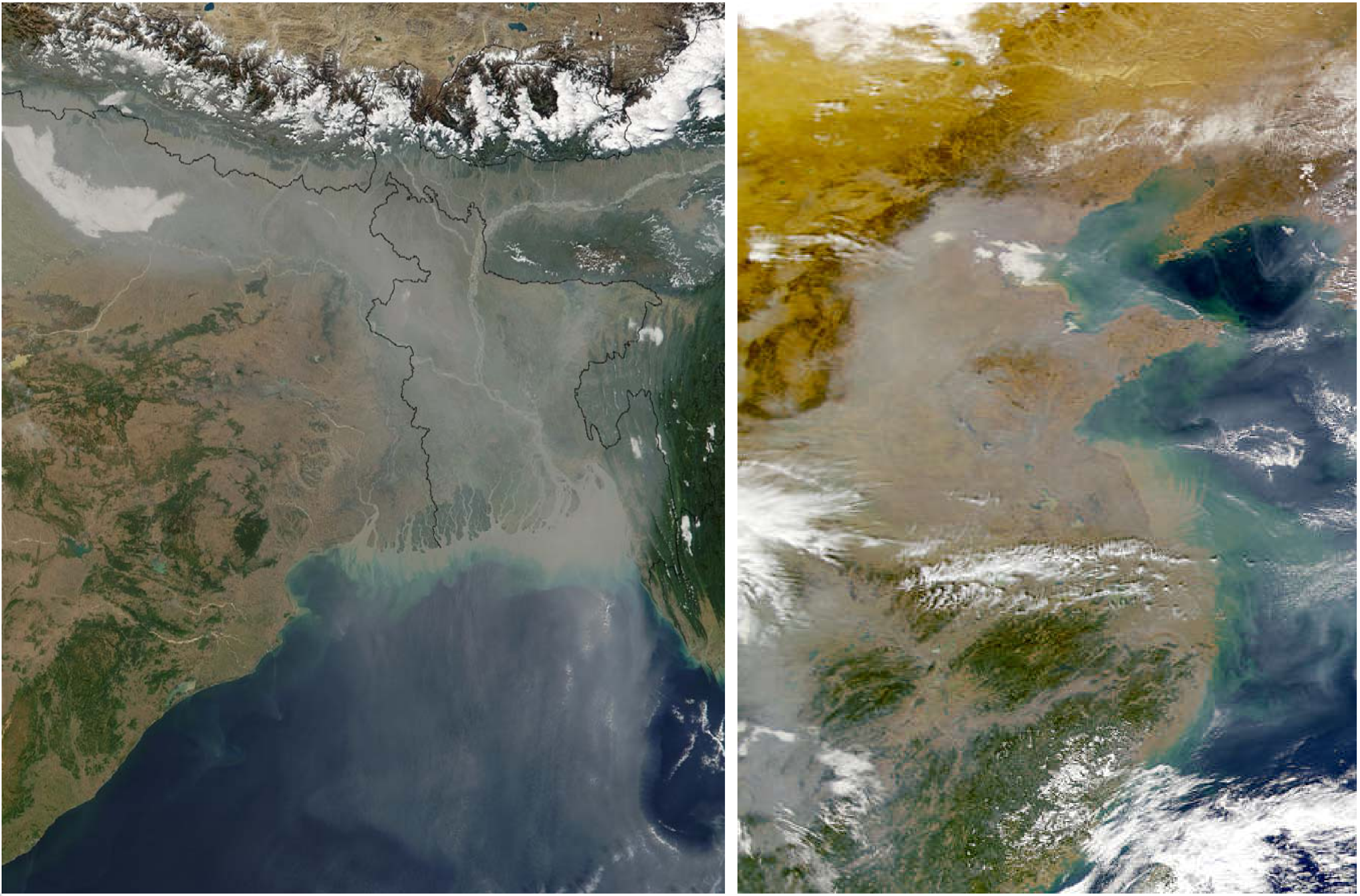


A massive sandstorm blowing off the northwest African desert has blanketed hundreds of thousands of square miles of the eastern Atlantic Ocean with a dense cloud of Saharan sand. The massive nature of this particular storm was first seen in this SeaWiFS image acquired on Saturday, 26 February 2000 when it reached over 1000 miles into the Atlantic. These storms and the rising warm air can lift dust 15,000 feet or so above the African deserts and then out across the Atlantic, many times reaching as far as the Caribbean where they often require the local weather services to issue air pollution alerts as was recently the case in San Juan, Puerto Rico. Recent studies by the U.S.G.S.(http://catbert.er.usgs.gov/african_dust/) have linked the decline of the coral reefs in the Caribbean to the increasing frequency and intensity of Saharan Dust events. Additionally, other studies suggest that Sahalian Dust may play a role in determining the frequency and intensity of hurricanes formed in the eastern Atlantic Ocean (http://www.thirdworld.org/role.html)

Provided by the SeaWiFS Project, NASA/GSFC and ORBIMAGE

http://www.earth.nasa.gov

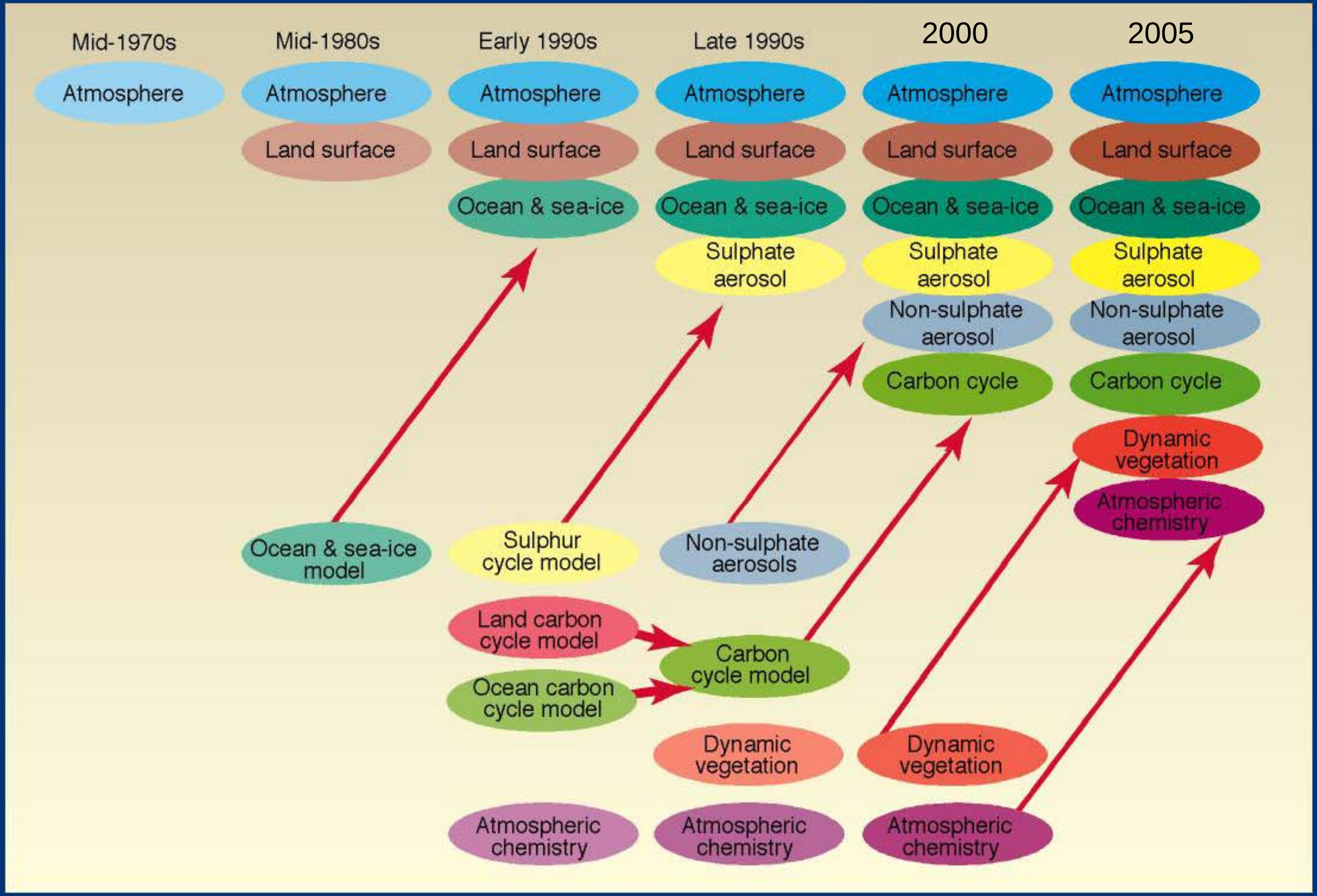
Energy Budget Impacts of Atmospheric Aerosol



http://www.earth.nasa.gov

Climate Model 'Evolution'

The development of climate models, past, present and future



WG1 - TS BOX 3
FIGURE 1

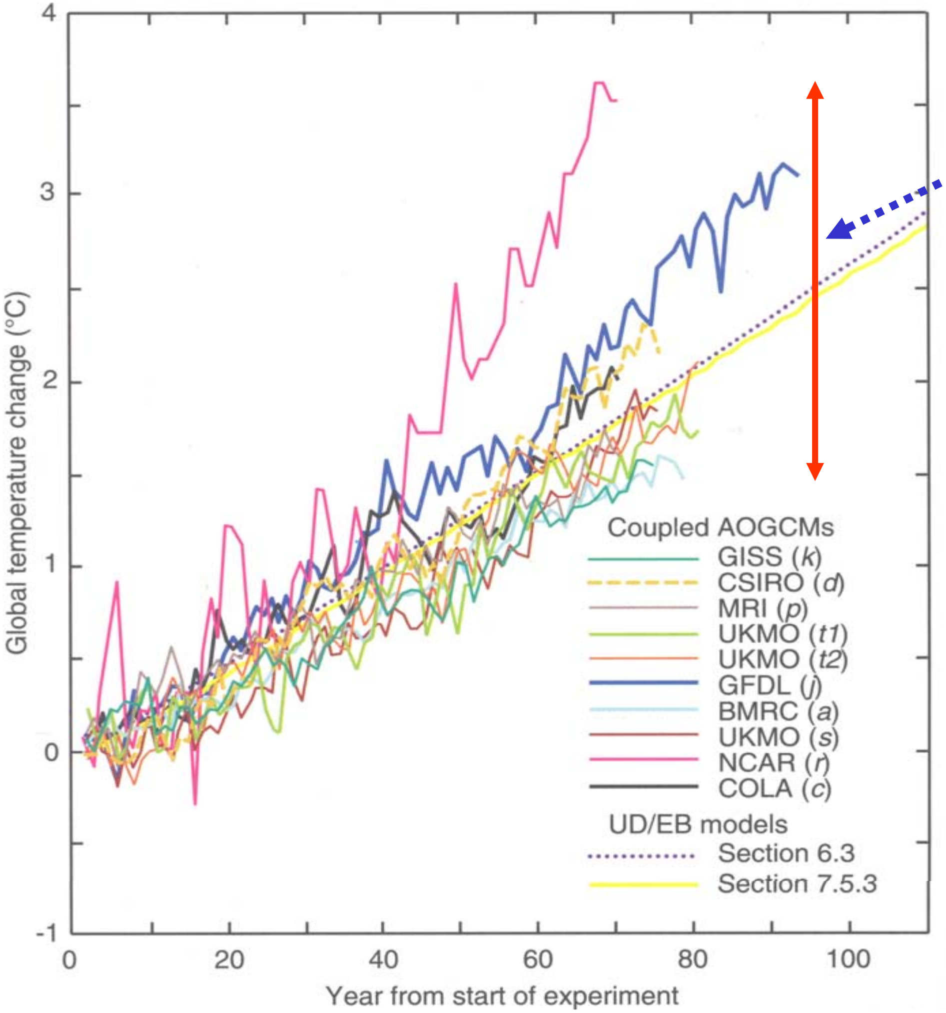
1x 3x 20x

The Computational Efficiency Challenge

- Heterogeneous collection of irregular algorithms
  - diverse collection of algorithms (physical/dynamical/chemical processes)
- Relatively low-resolution configurations
  - severely limits scalability; parallelism grows slower than op count
- Use of non-local techniques
  - employed for numerical efficiency, inherently communication intensive
- Need for long integration periods
  - physical time scales decades to centuries
- *Efficient* implementations for volatile computational environments
  - immature development and production environments
  - sub-optimally balanced hardware infrastructure

Participation in Community Exercises

IPCC 1995: Climate Model Projections



Uncertainty presents scientific and political problem

Has not changed much in last few decades

Extension of physical climate system may exacerbate uncertainty

Summary

- Global Climate Modeling
  - complex and evolving scientific problem
  - parameterization of physical processes is pacing progress
  - observational limitations are pacing process understanding
  - computational limitations pacing exploration of model formulations
- Time for more comprehensive exploration of “spectral gap?”
  - exploration of scale interactions using modeling and observation
  - ultra-high resolution global simulations (~10^7x present)
  - super-parameterization (MMF) approach (~200x-500x)
  - high-resolution process modeling to supplement observations
    - identify optimal truncation strategies for capturing major scale interactions
    - better characterize statistical relationships between resolved & unresolved scales

The End