

How Computational Capability[†] is Pacing the Realistic Simulation of Earth's Climate System

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[†] *It's just one among many pacing items, but an important one!*

Outline

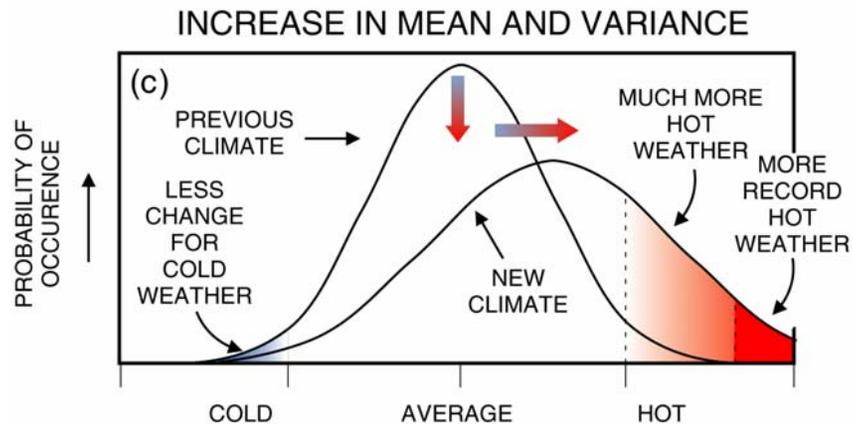
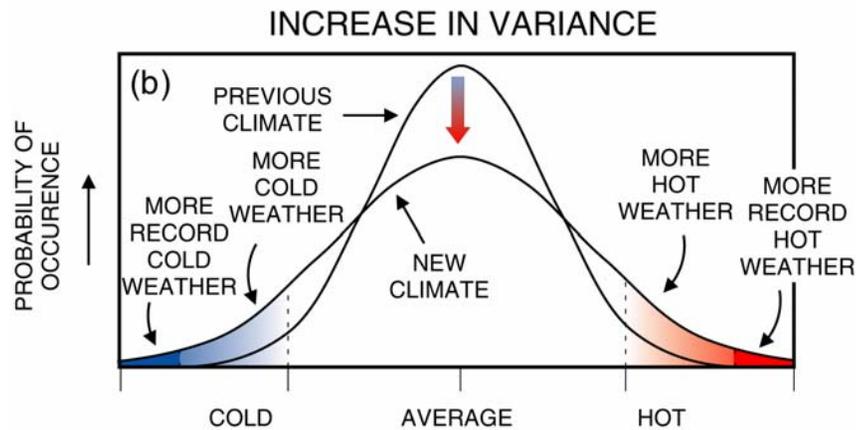
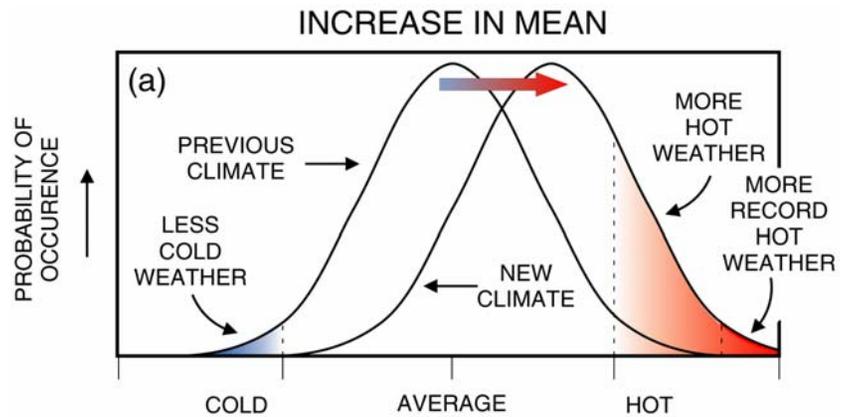
- Overview of the problem
- Characterize the approach to the problem
 - illustrate issue of truncation
 - illustrate uncertainties associated with non-resolvable motion field
 - illustrate the likely importance of scale interaction
- Show why resolution is only part of the problem
 - a necessary but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

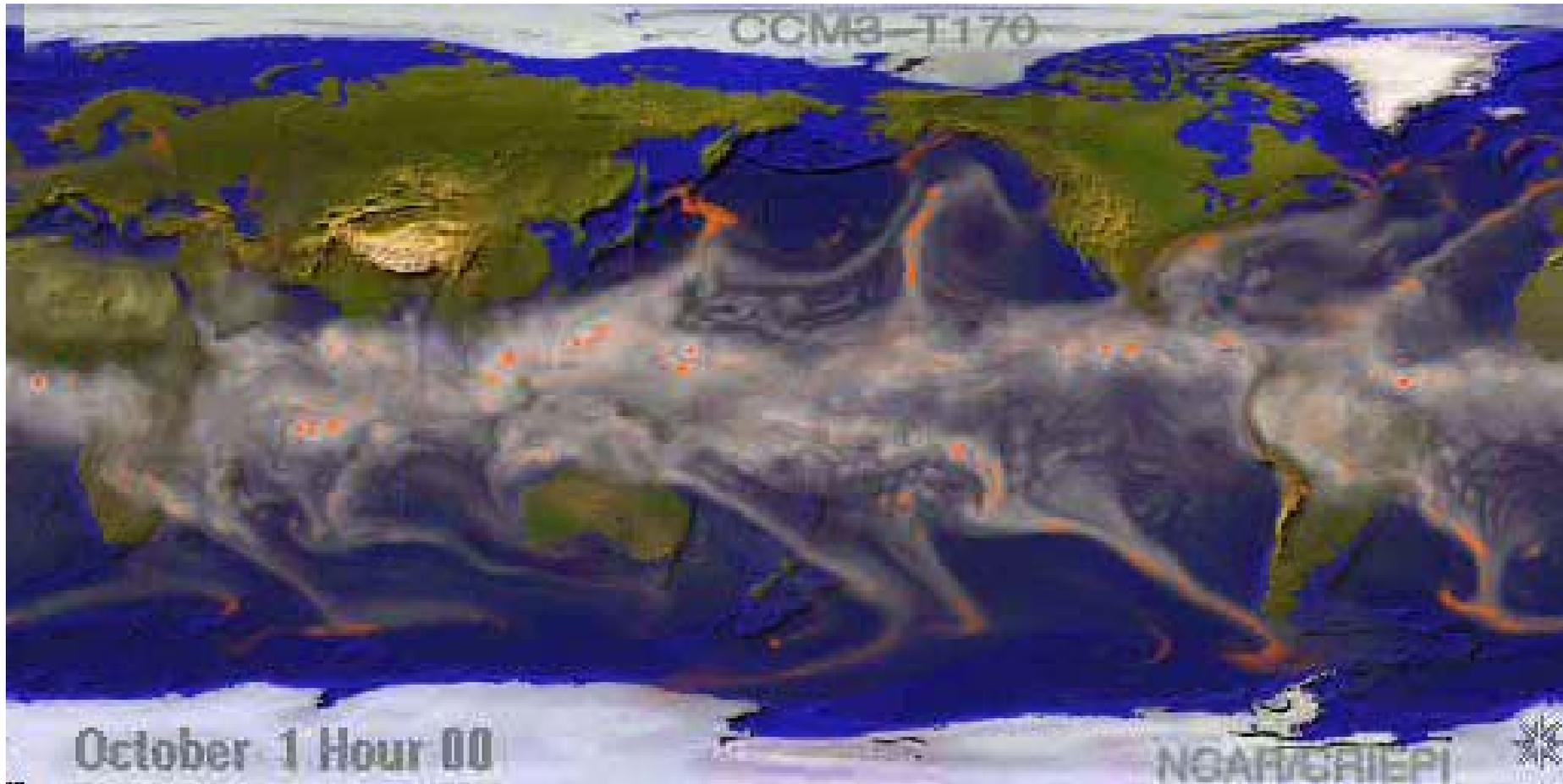
All of the above!

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



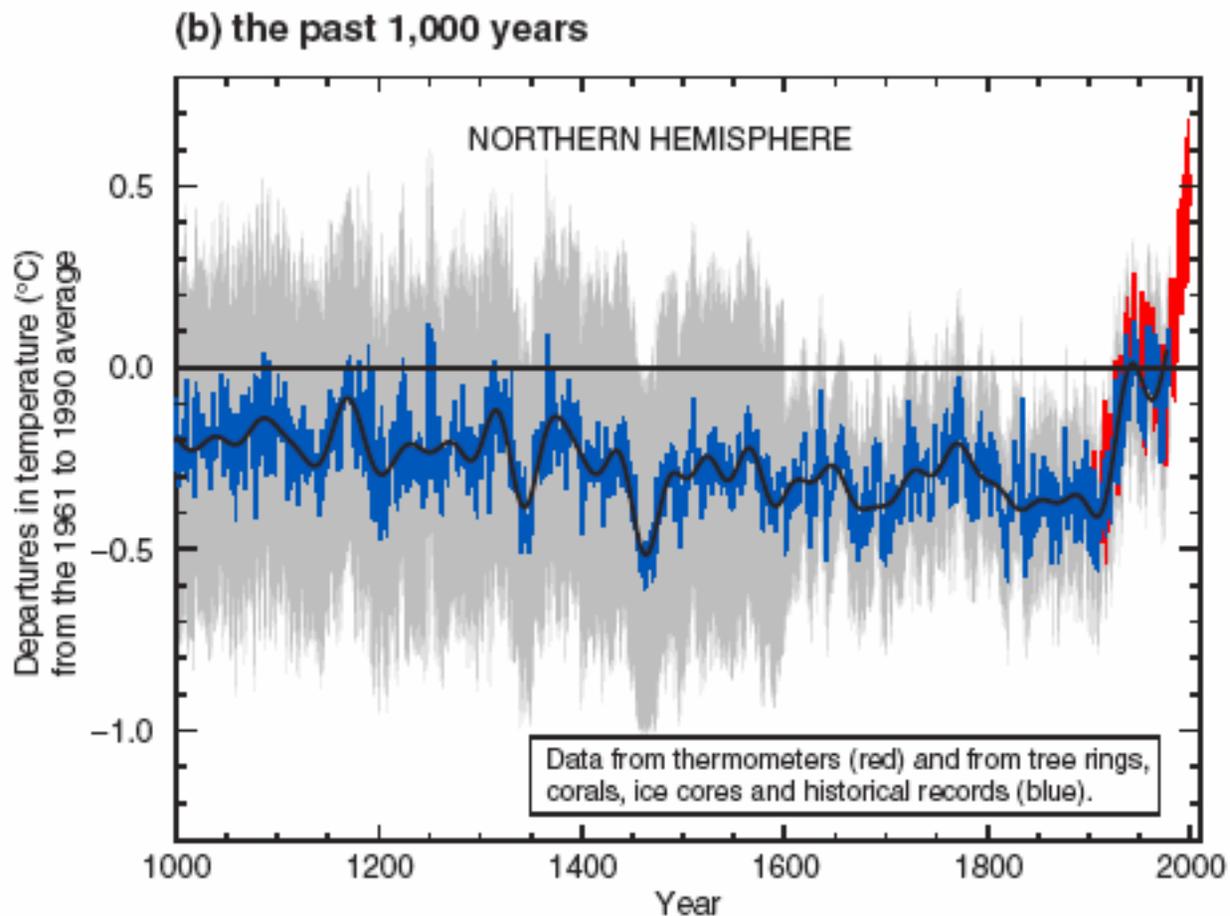
Example of Global Climate Model Simulation

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



Animation courtesy of NCAR SCD Visualization and Enabling Technologies Section

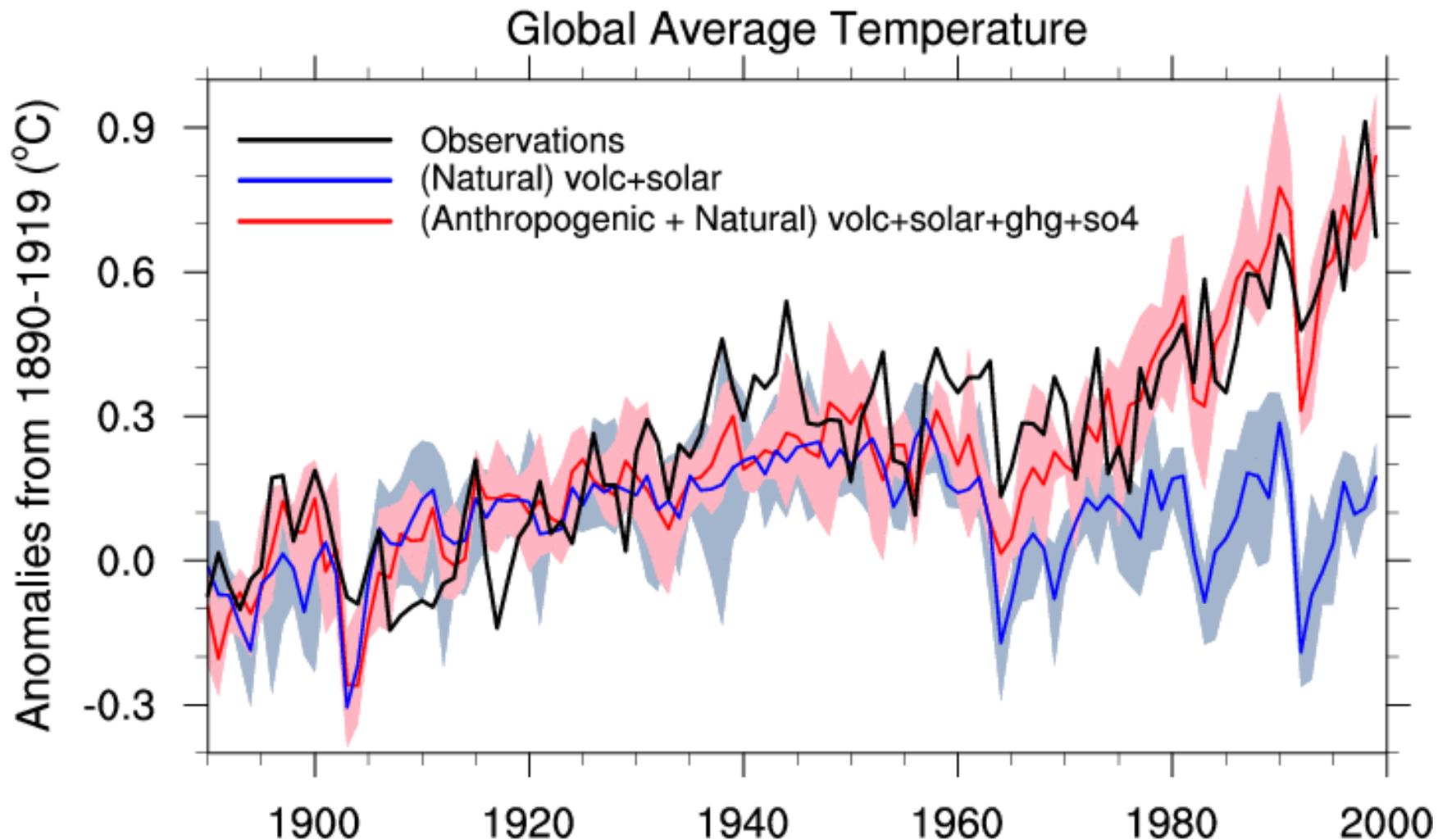
Observed Temperature Records



IPCC, 3rd Assessment, Summary For Policymakers

Observations: 20th Century Warming

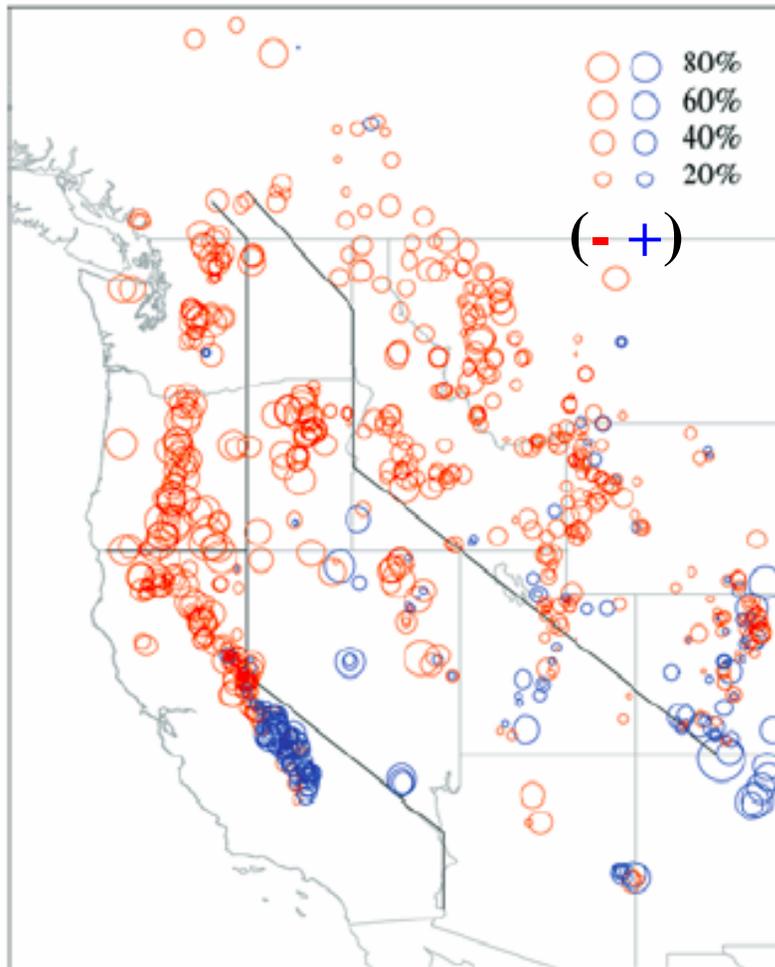
Model Solutions with Human Forcing



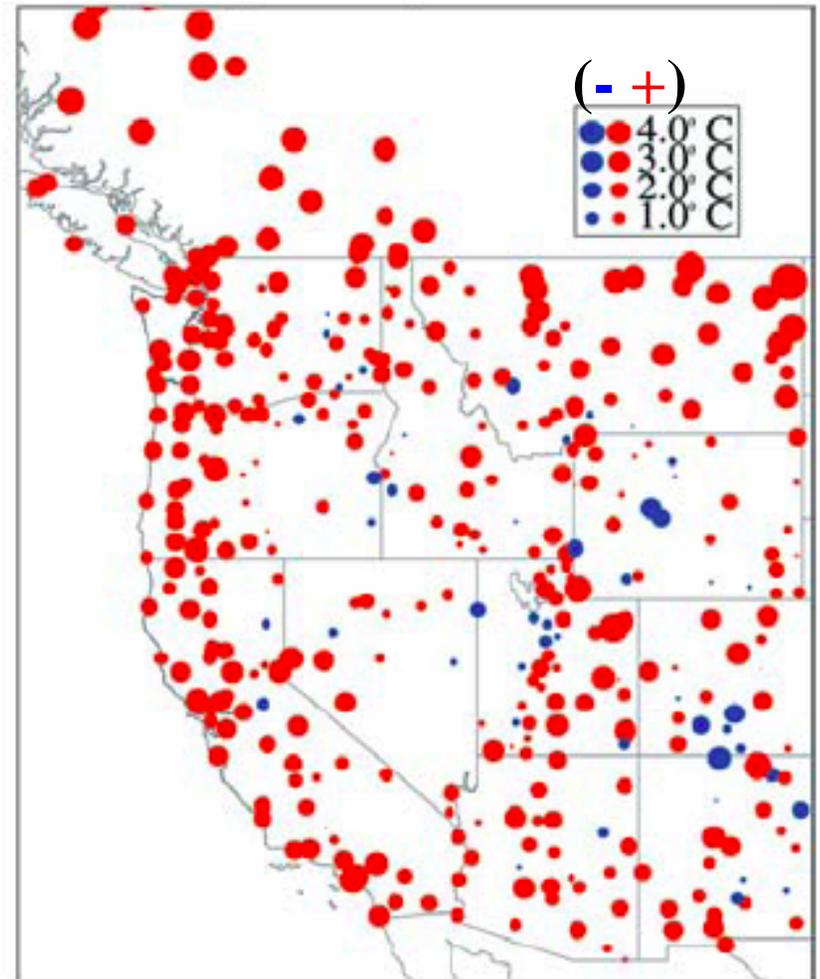
Impacts of Climate Change

Observed Change 1950-1997

Snowpack



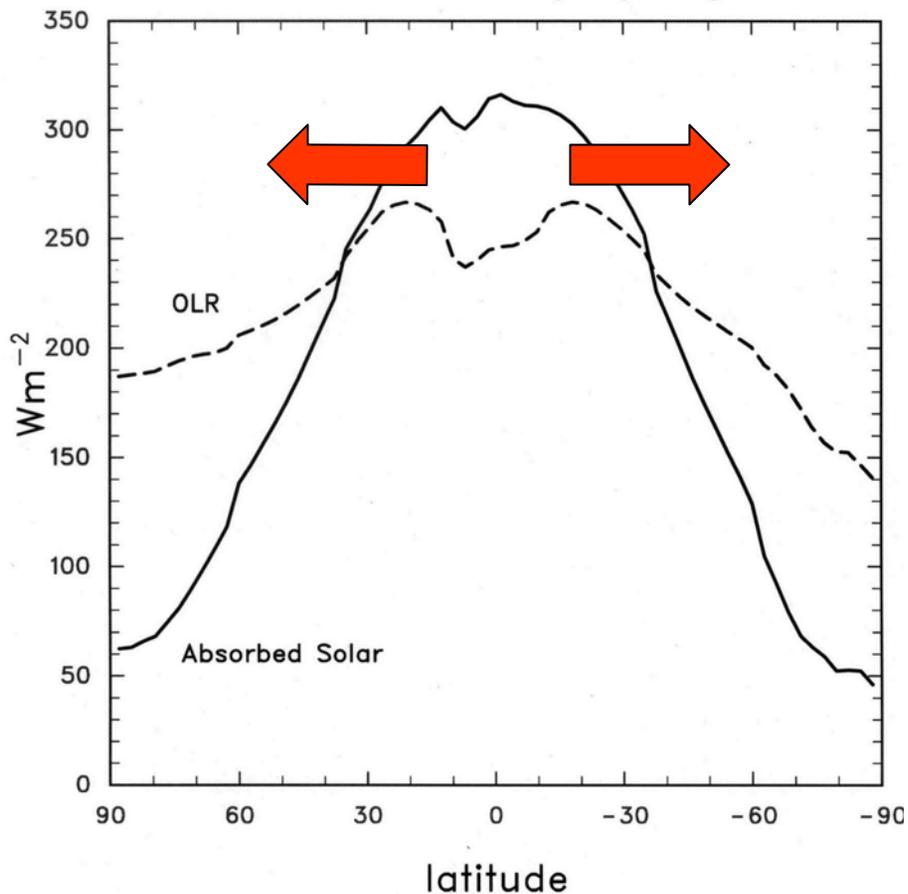
Temperature



Energy Balance: Fundamental Driver of the Scientific Problem

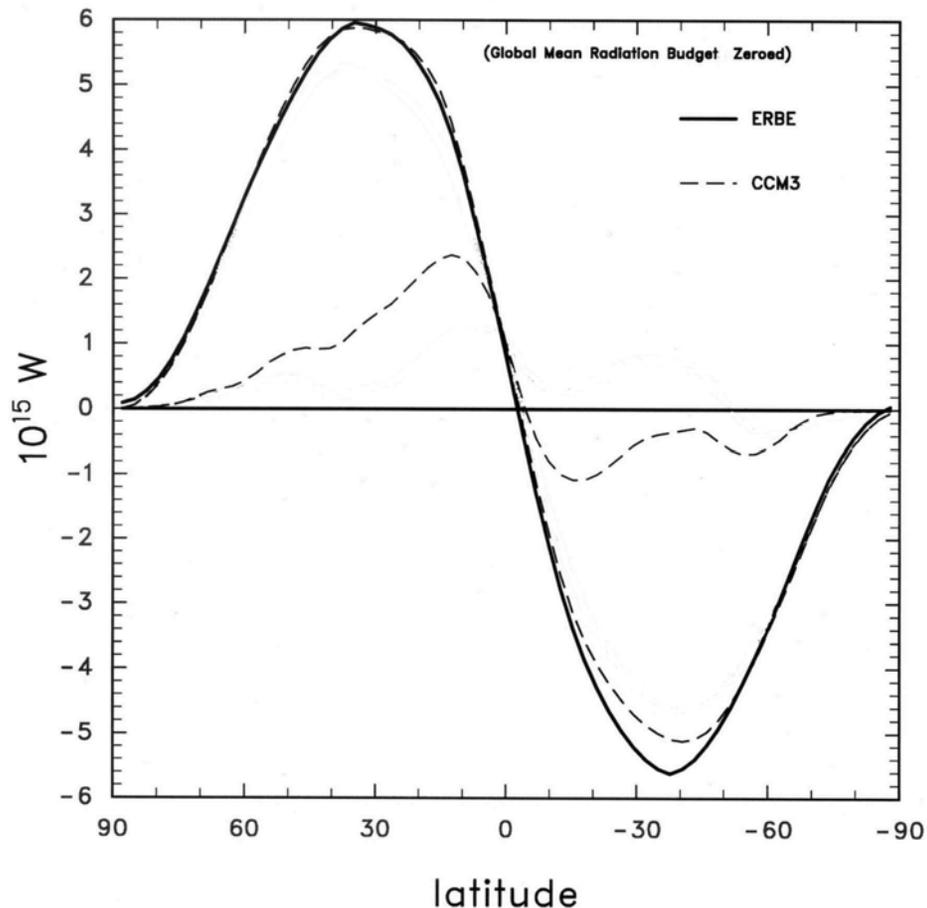
Longwave and Shortwave Energy Budget

ERBE Absorbed Solar and Outgoing Longwave Fluxes:

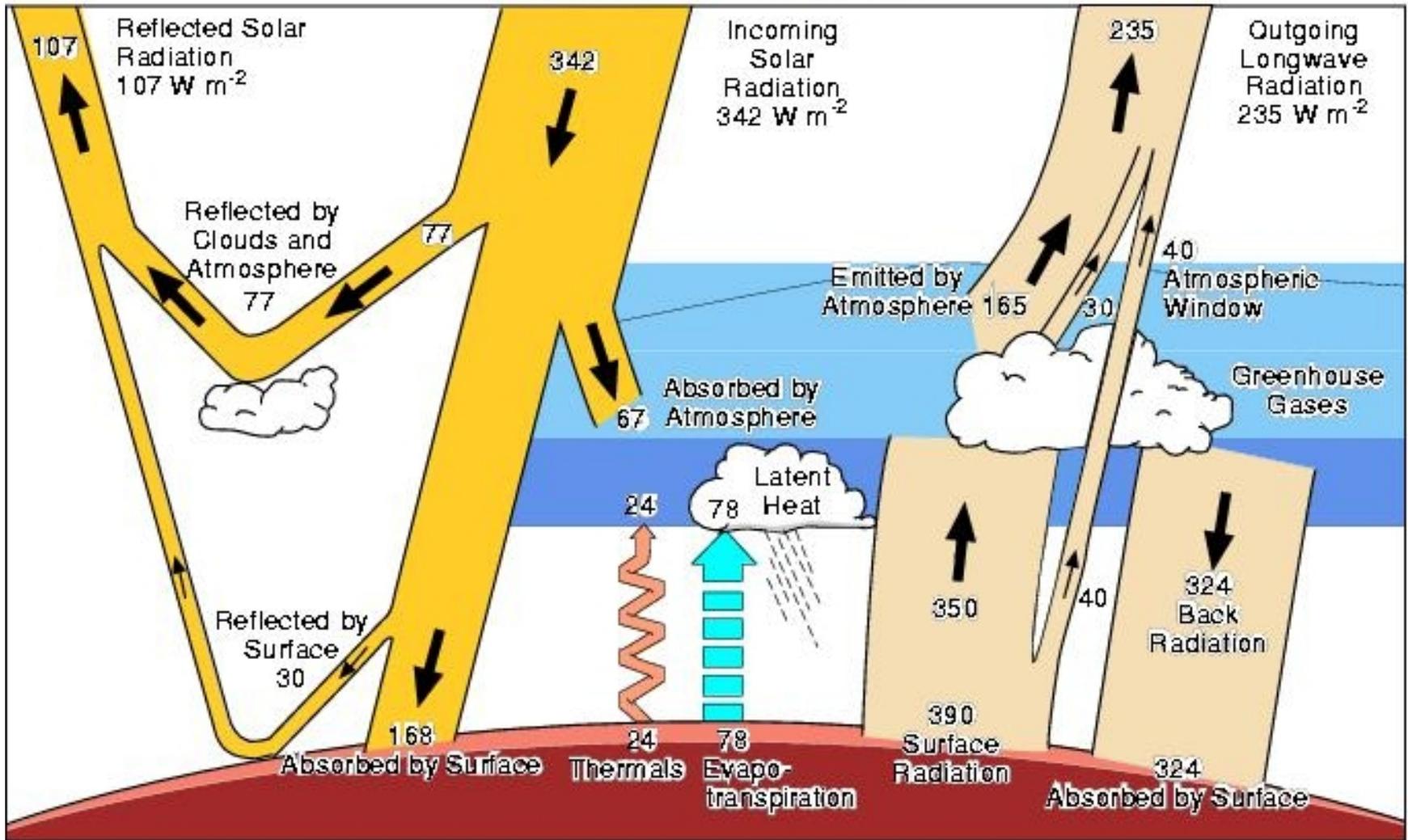


Northward Energy Transport

Mean Annual Transport: CCM3



Global Heat Flows

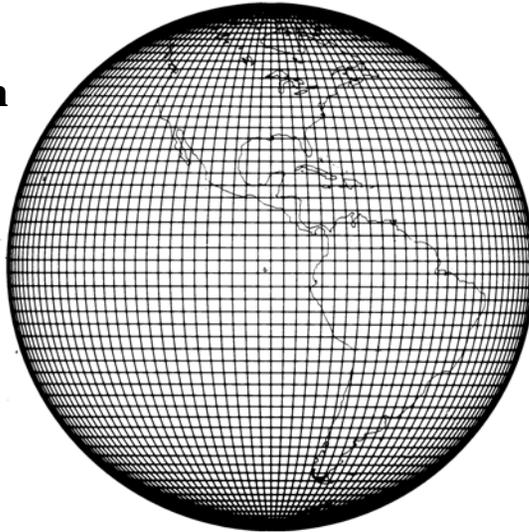


Kiehl and Trenberth 1997

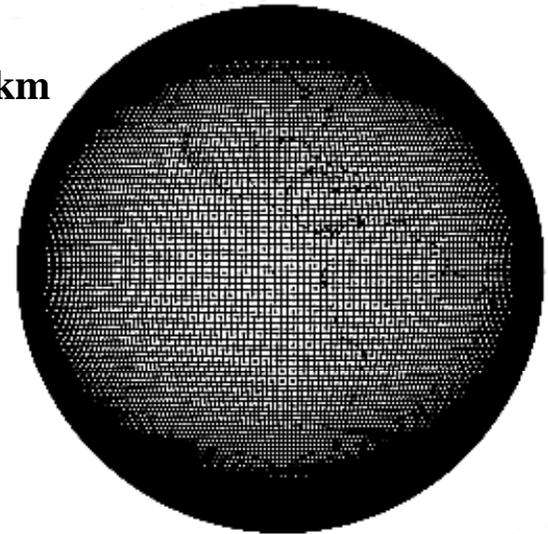
Computational Balancing Act

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

$\Delta x = 300$ km

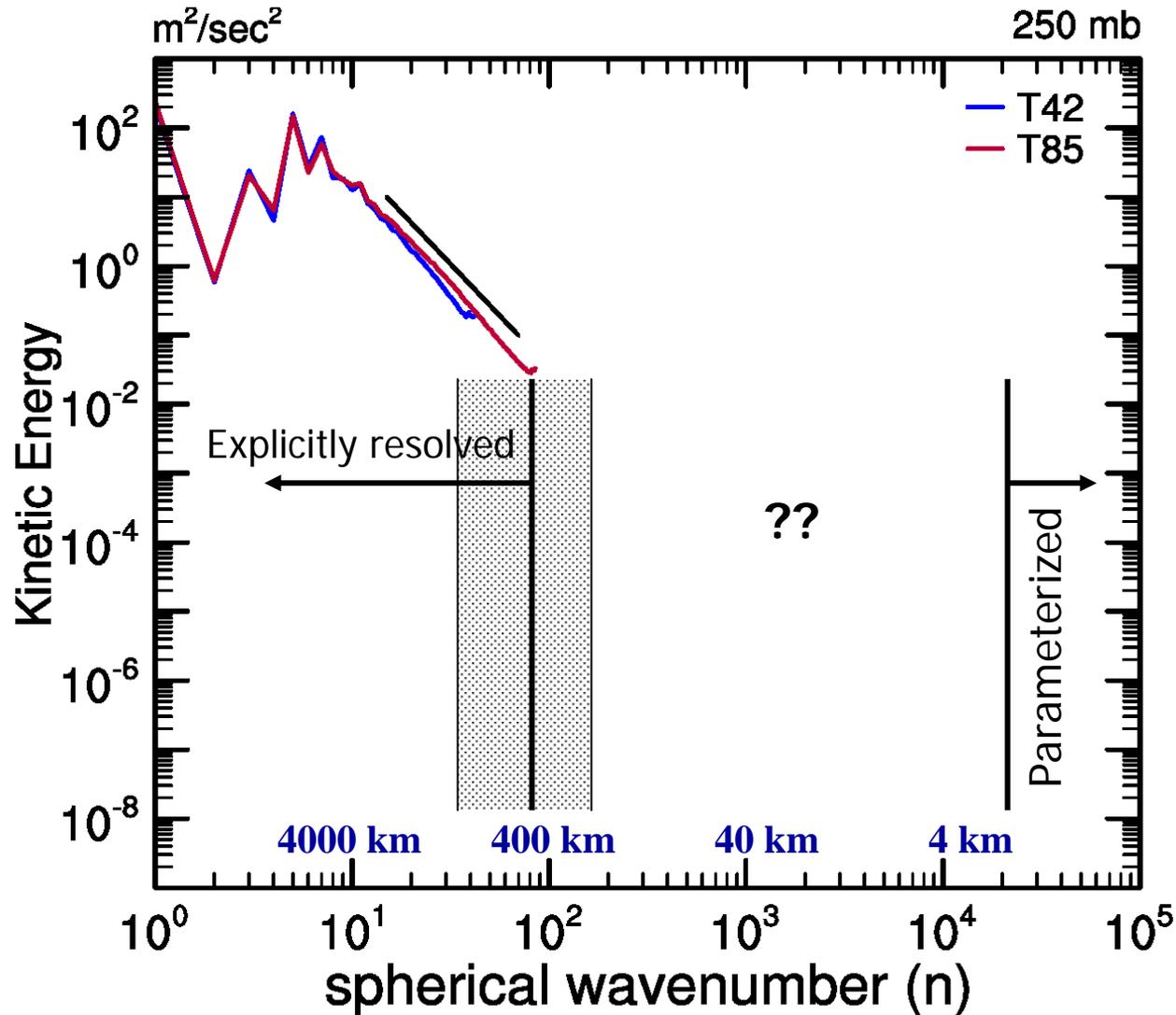


$\Delta x = 150$ km

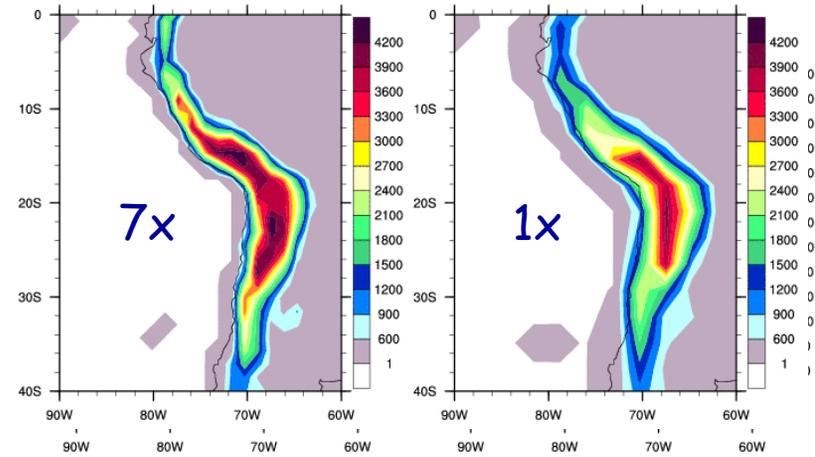
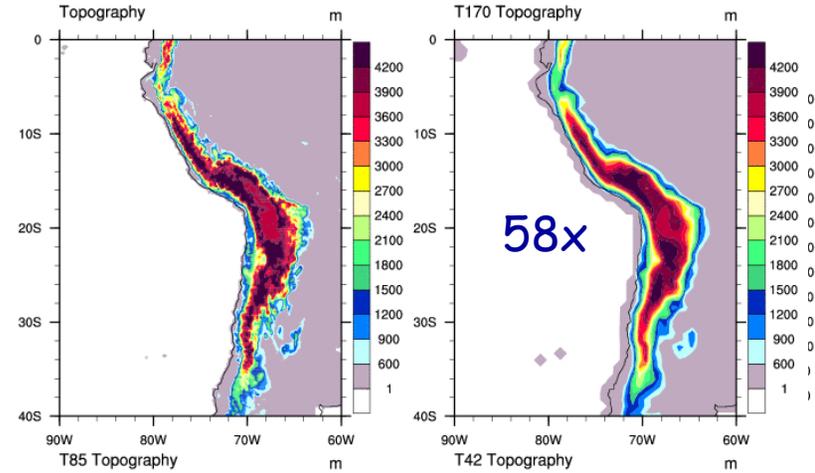
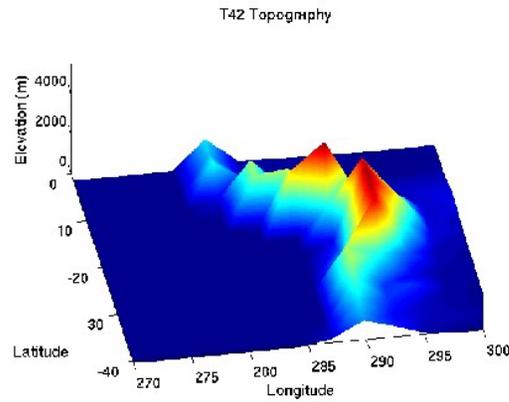
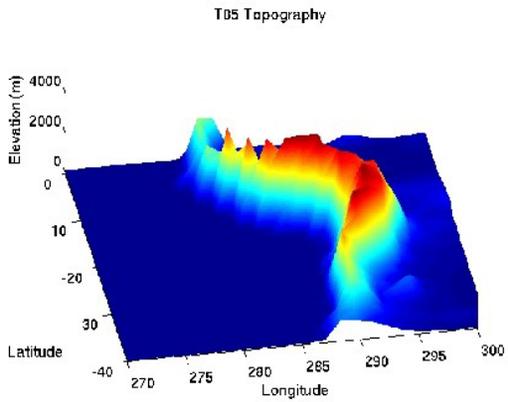
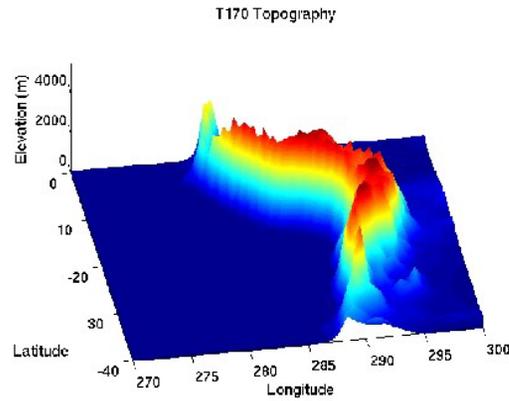
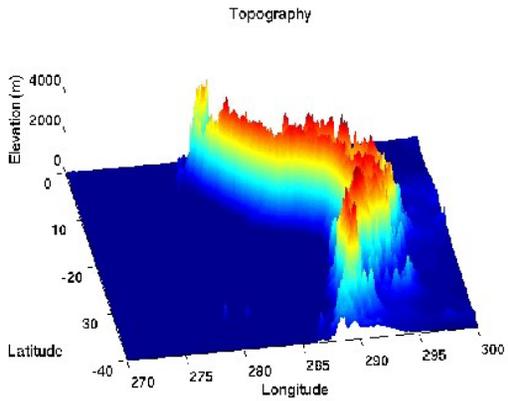


- Long integration times/ensembles required for climate
 - non-deterministic problem with large natural variability
 - long equilibrium time scales for coupled systems
 - *computational capability 0th-order rate limiter*

Atmospheric Motion Scales and Parameterization

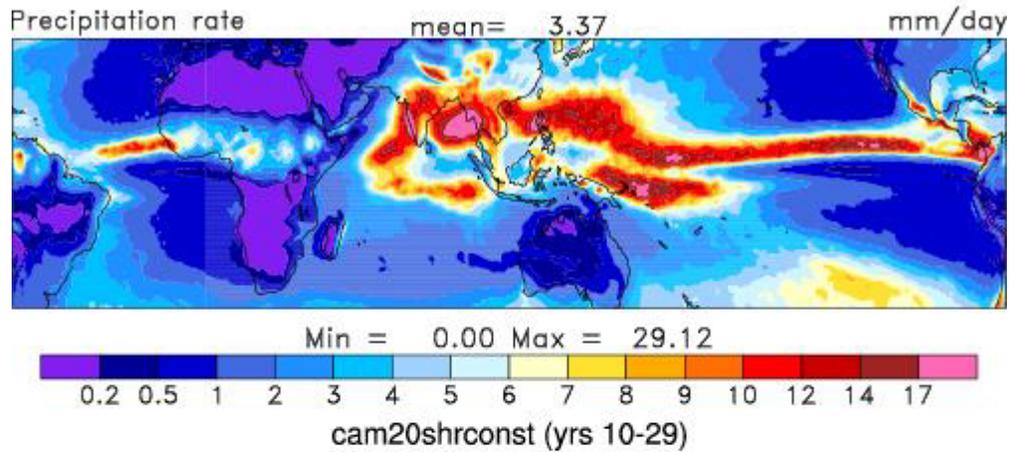


Global Modeling and Horizontal Resolution

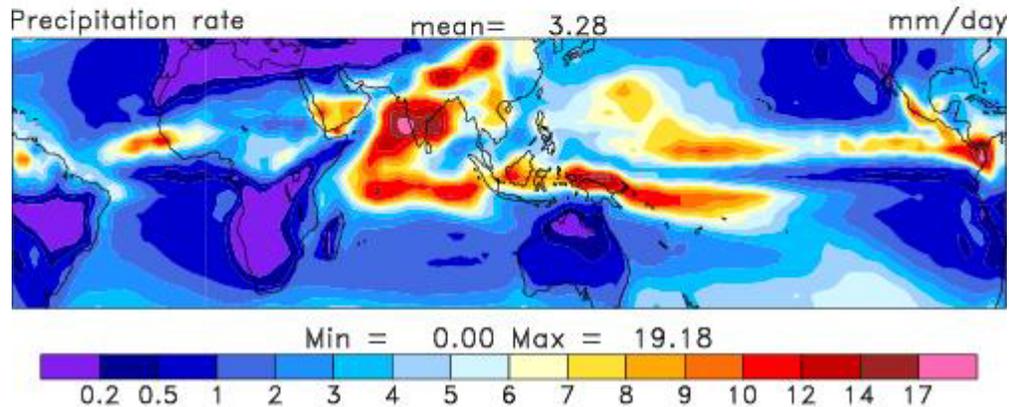


Simulation Improvements in Mean Measures

high-resolution



standard



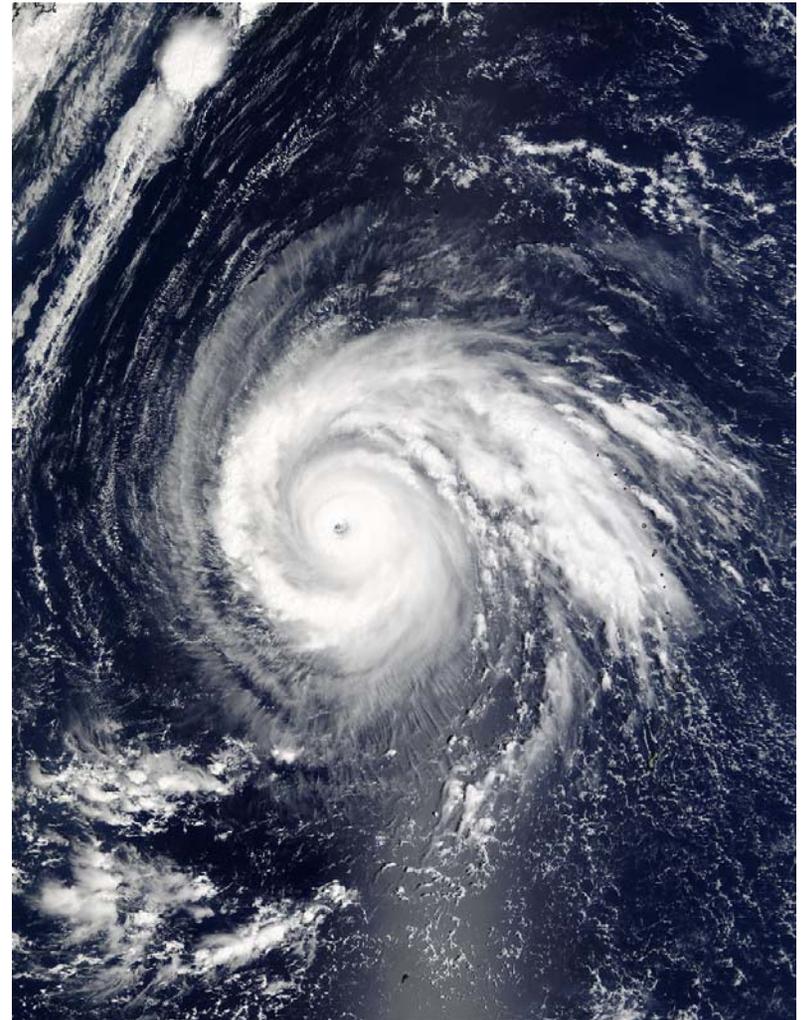
Atmospheric Energy Transport

Synoptic-scale mechanisms

- extratropical storms



- hurricanes



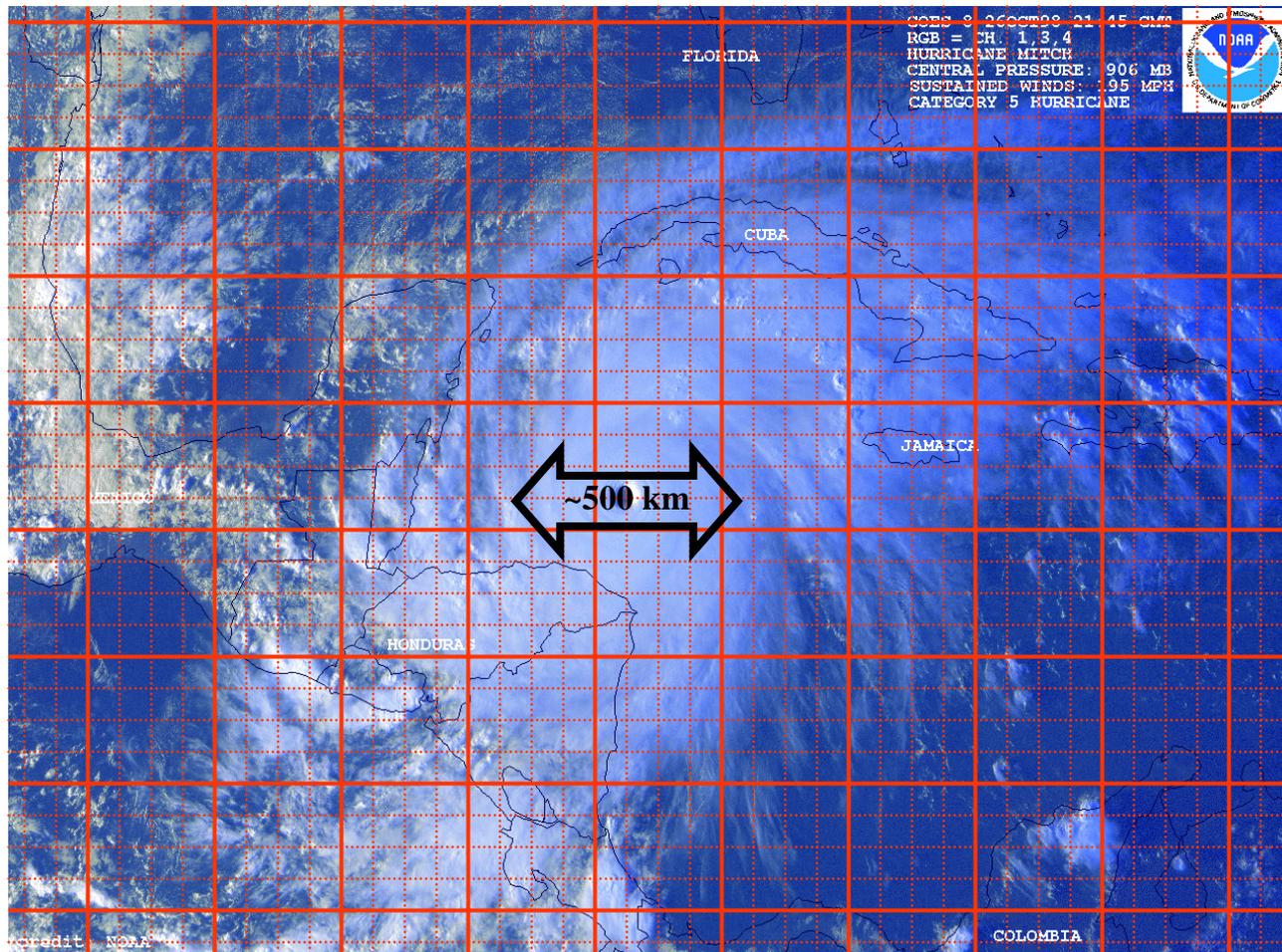
Capturing Primary Phenomenological Scales of Motion in Global Models

Simulation of Tropical Cyclone Impacts on Climate



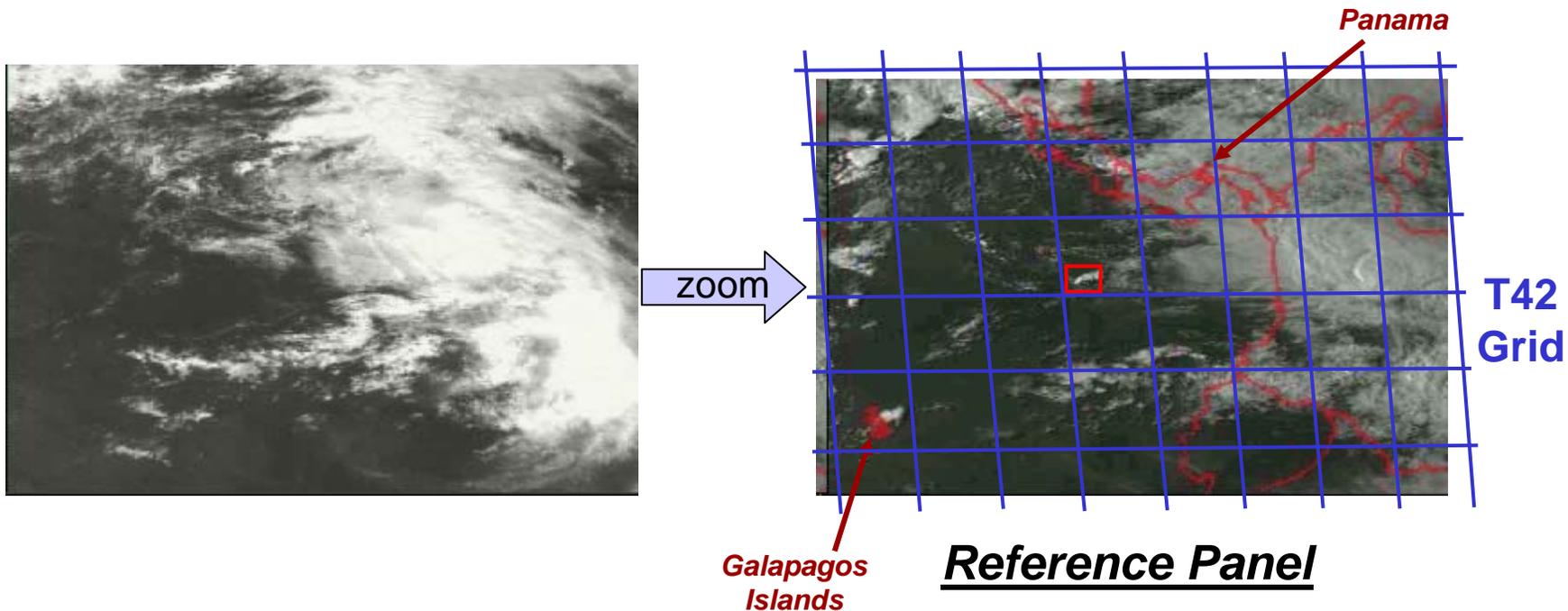
High-Resolution Global Modeling

Simulation of Tropical Cyclone Impacts on Climate

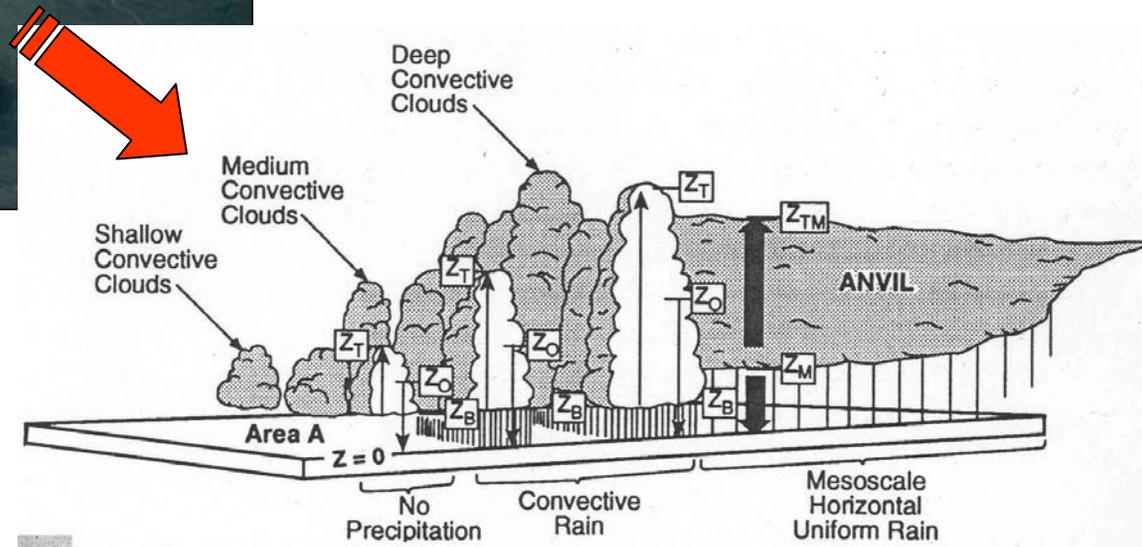
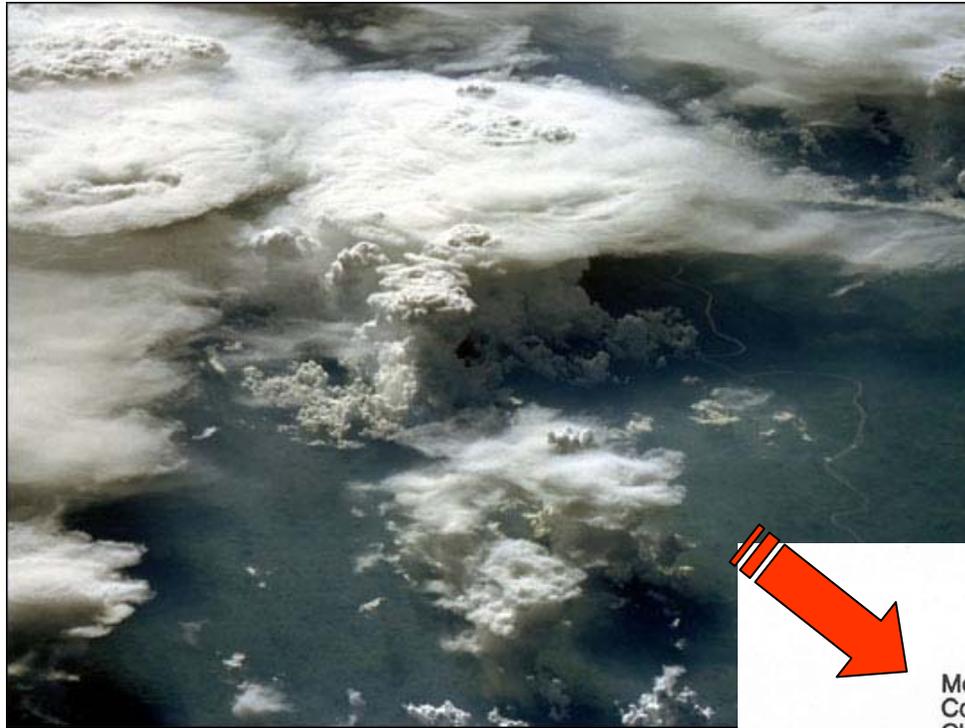


High-Resolution Global Modeling

Still a Need to Treat Subgrid-Scale Processes



Process Models and Parameterization



Does Resolution Matter at the Process Level?

Moist Convection Example

Heat

$$\frac{\partial \bar{s}}{\partial t} = \underbrace{-\nabla \cdot \bar{\mathbf{V}}_s - \frac{\partial \bar{\omega} \bar{s}}{\partial p}}_{\text{resolved}} \underbrace{- \frac{\partial}{\partial p} (\overline{\omega' s'}) + L\mathcal{R} + c_p Q_R}_{\text{parameterized}}$$

Moisture

$$\frac{\partial \bar{q}}{\partial t} = \underbrace{-\nabla \cdot \bar{\mathbf{V}}_q - \frac{\partial \bar{\omega} \bar{q}}{\partial p}}_{\text{resolved}} \underbrace{- \frac{\partial}{\partial p} (\overline{\omega' (q' + l')}) - \mathcal{R}}_{\text{parameterized}}$$

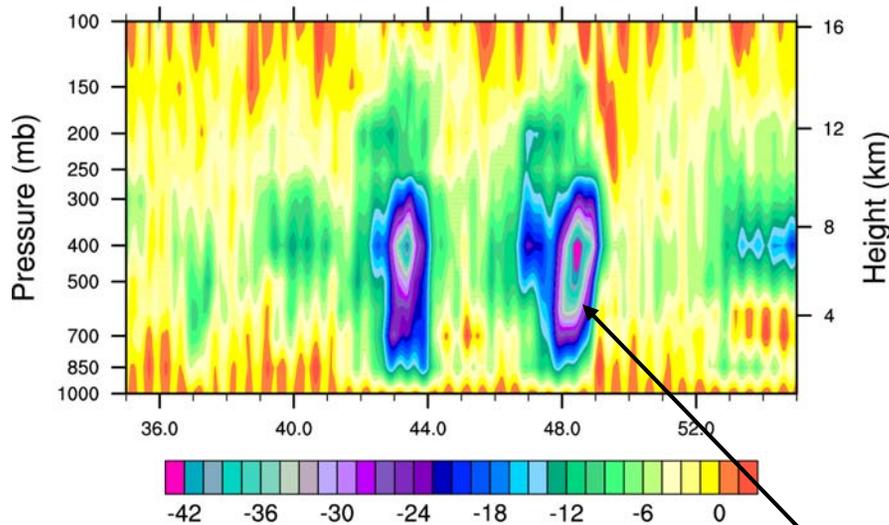
we resolve the
“large scale”

and parameterize the
unresolved scales

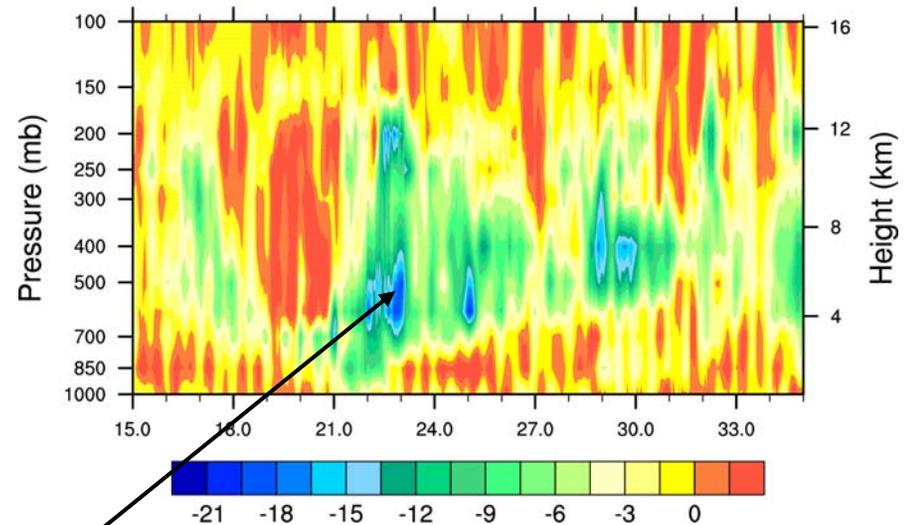
What happens to the “large-scale” motions seen by the parameterized physics as resolution is changed?

Warm Pool Temperature Forcing Time Series

T85 averaged to T42



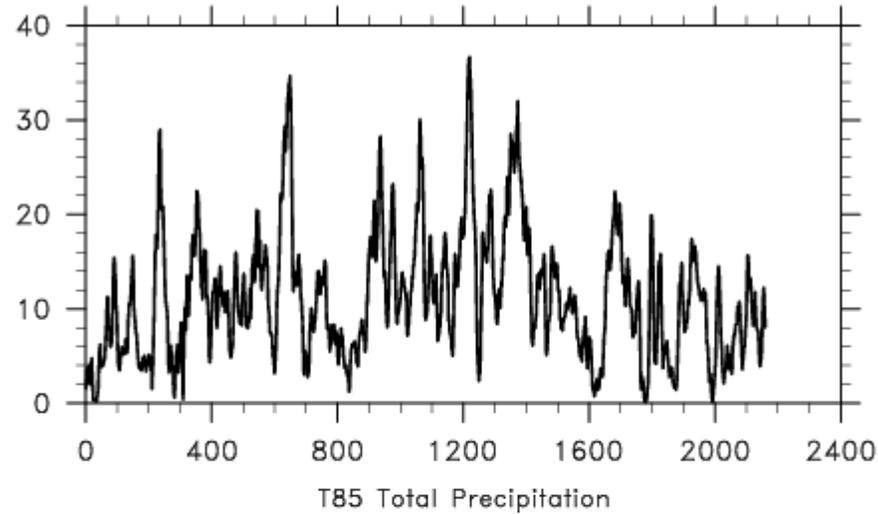
T42 (300 km)



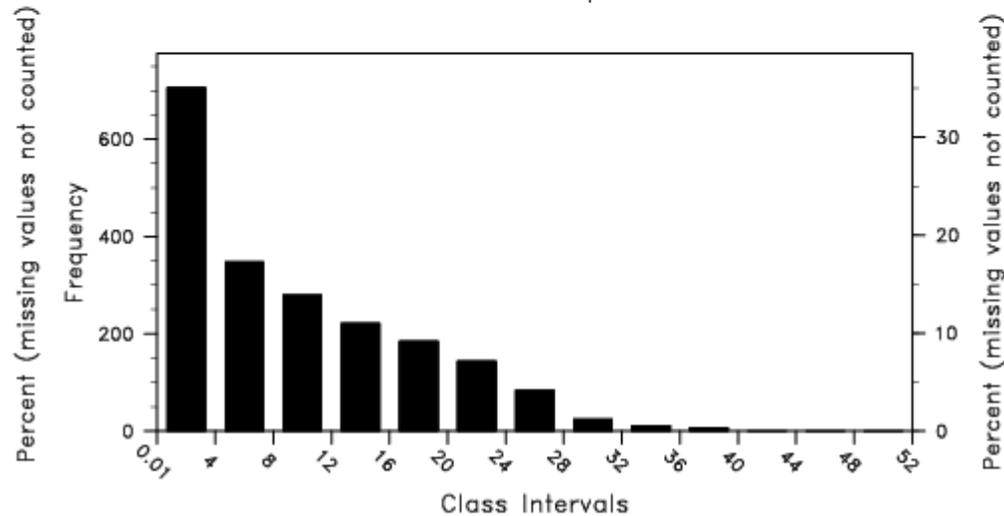
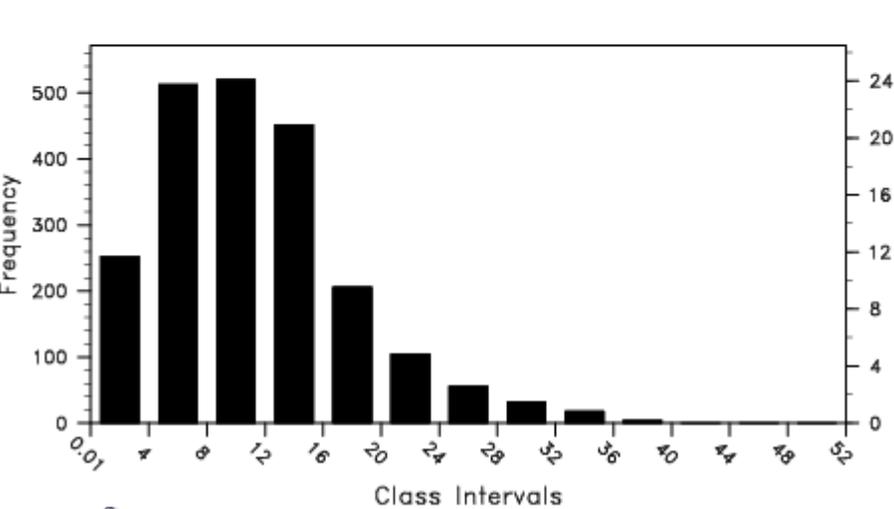
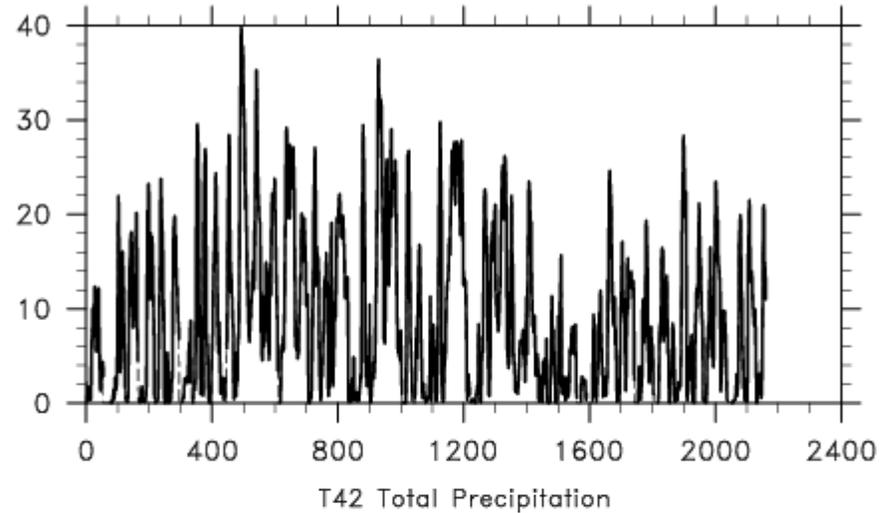
Fundamentally different “large-scale” forcing of parameterized physics

Warm Pool Precipitation Characteristics

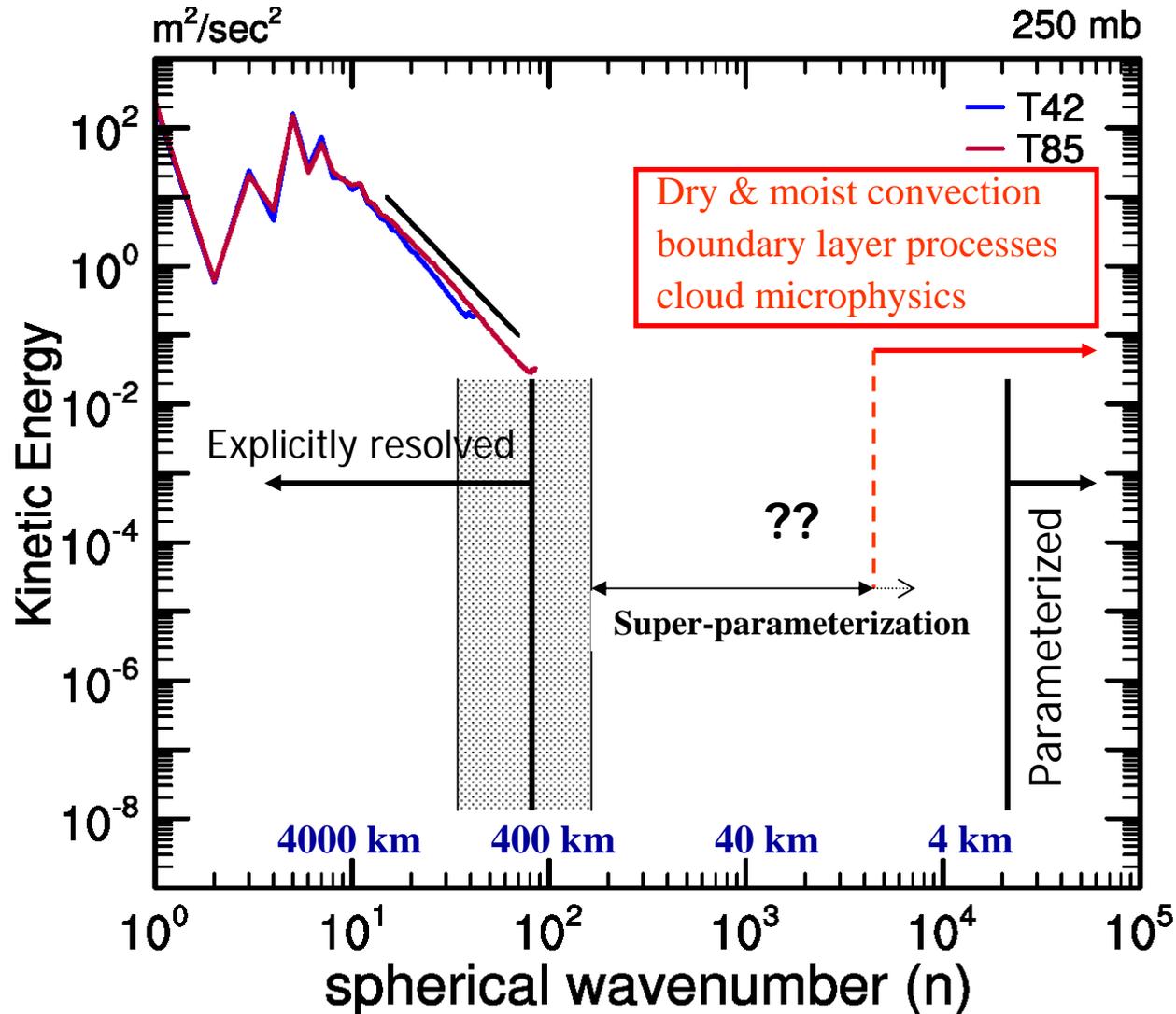
Precipitation (Mean=11.2484)



Precipitation (Mean=9.44408)



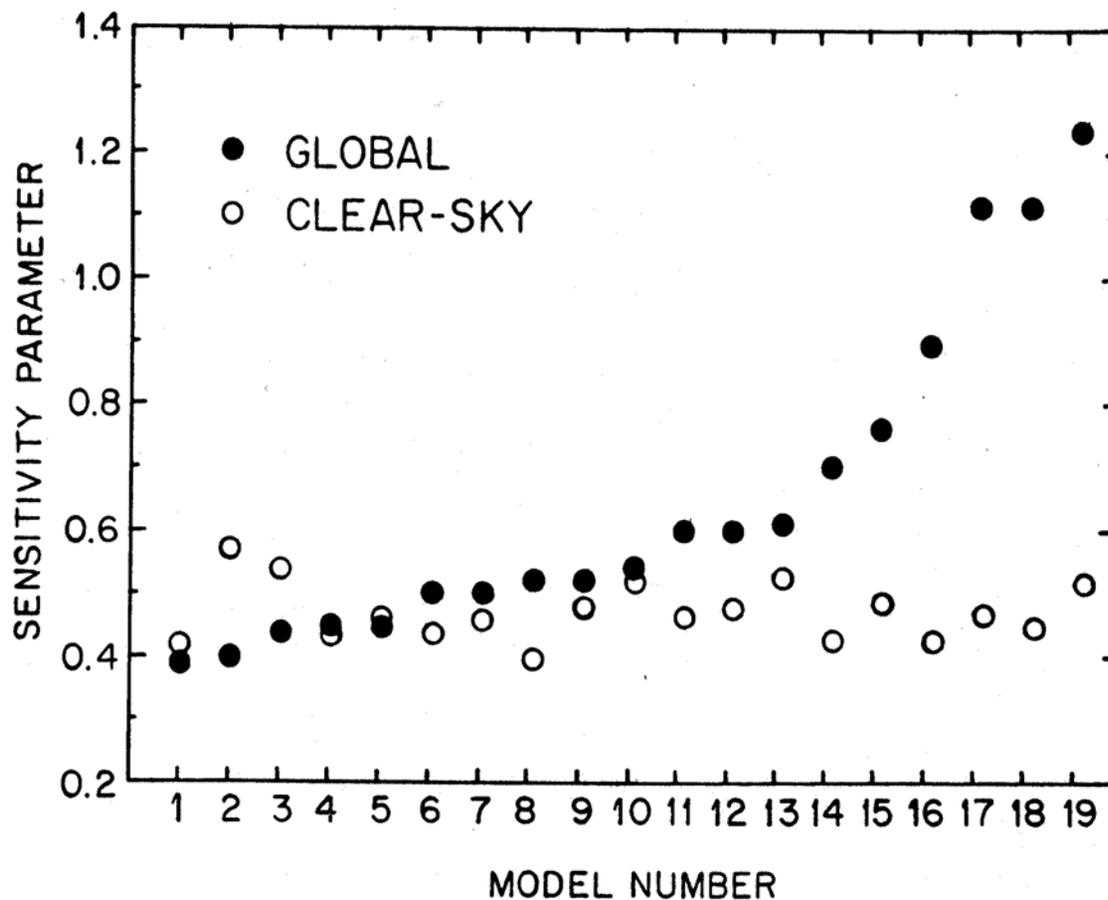
Atmospheric Motion Scales and Parameterization



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
 - *Carbon!!*

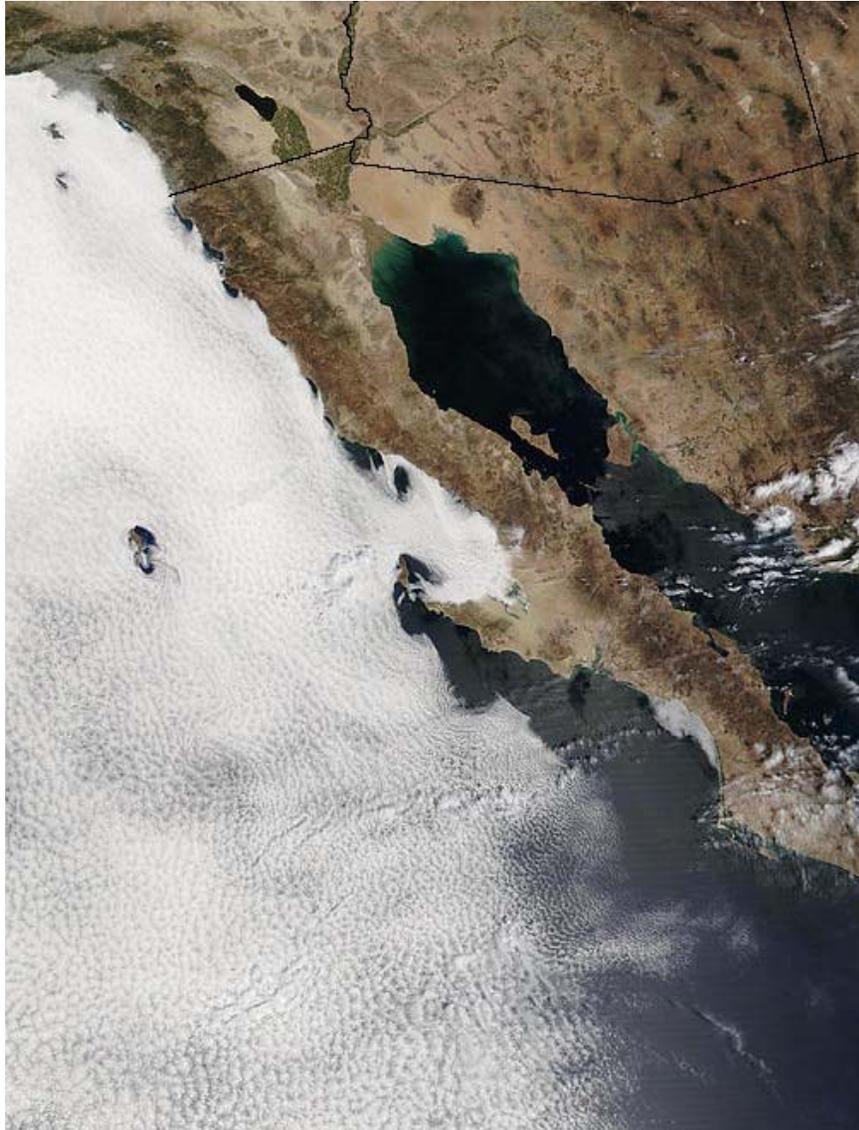
Parameterization of Clouds



Cess et al. (1990)

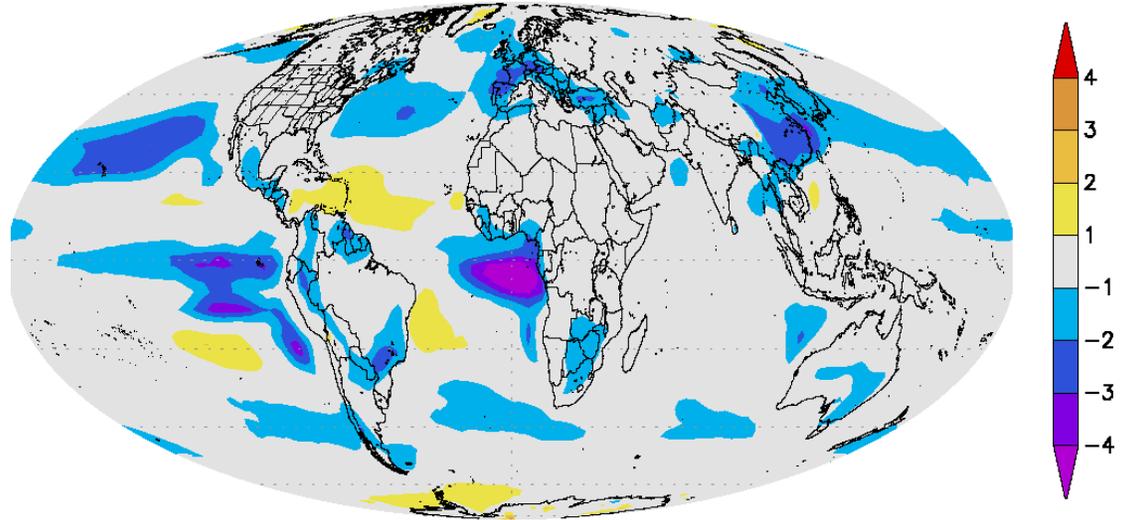
Fig. 1. Clear-sky and global sensitivity parameters ($\text{K m}^2 \text{W}^{-1}$) for the 19 GCMs. The model numbers correspond to the ordering in Table 9.

Marine Stratus: Low Clouds over the Ocean



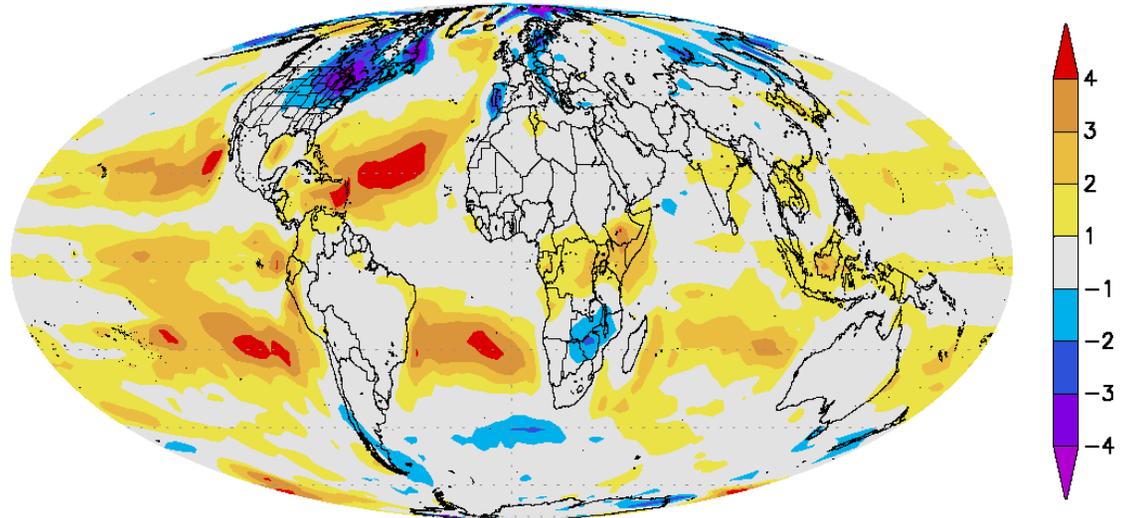
Low Clouds Over the Ocean

GFDL AM2-ML (2xCO₂ - CTRL)



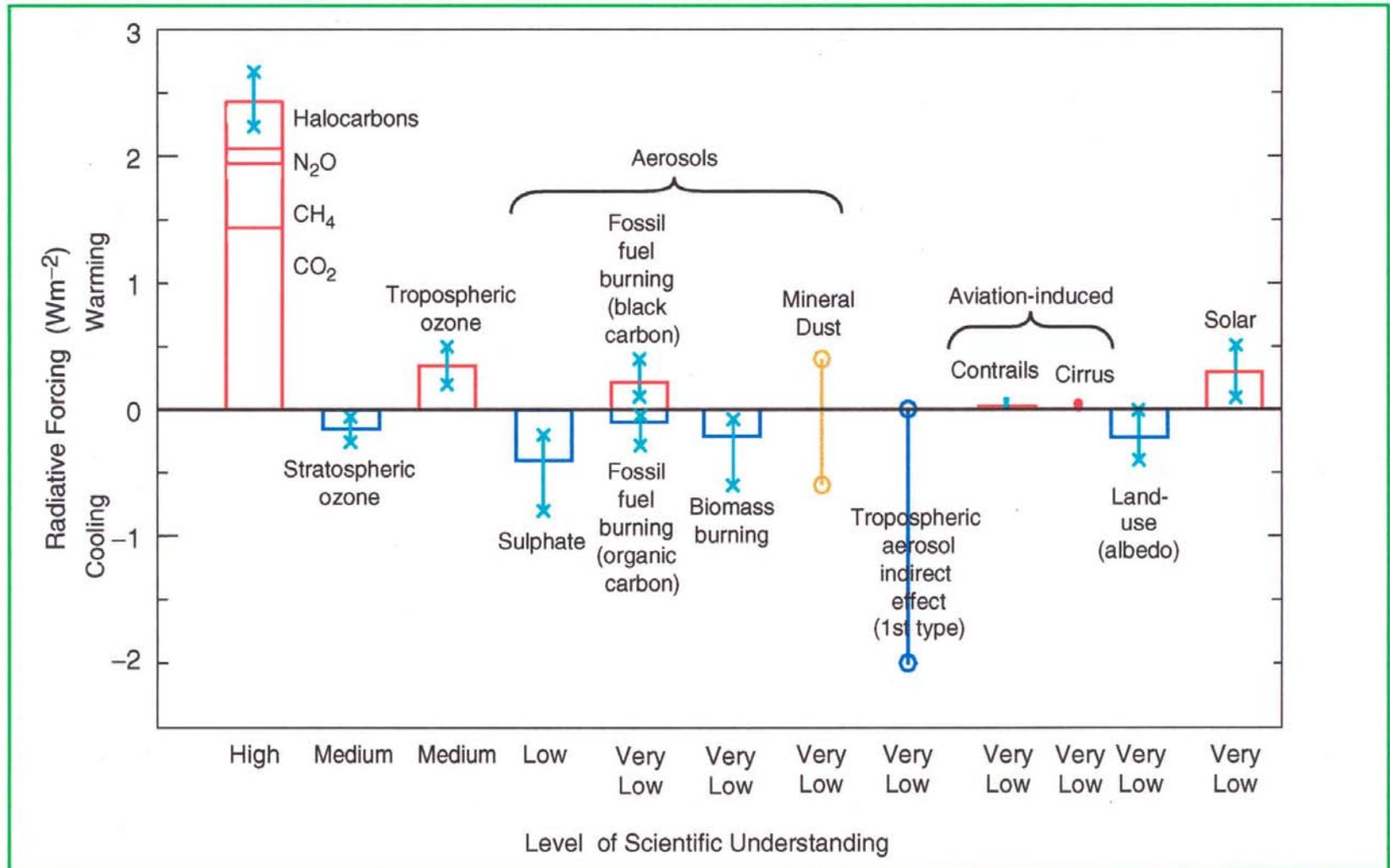
Two Models: Changes are OPPOSITE!

NCAR CAM2 (Year70 @1%CO₂/yr - CTRL)



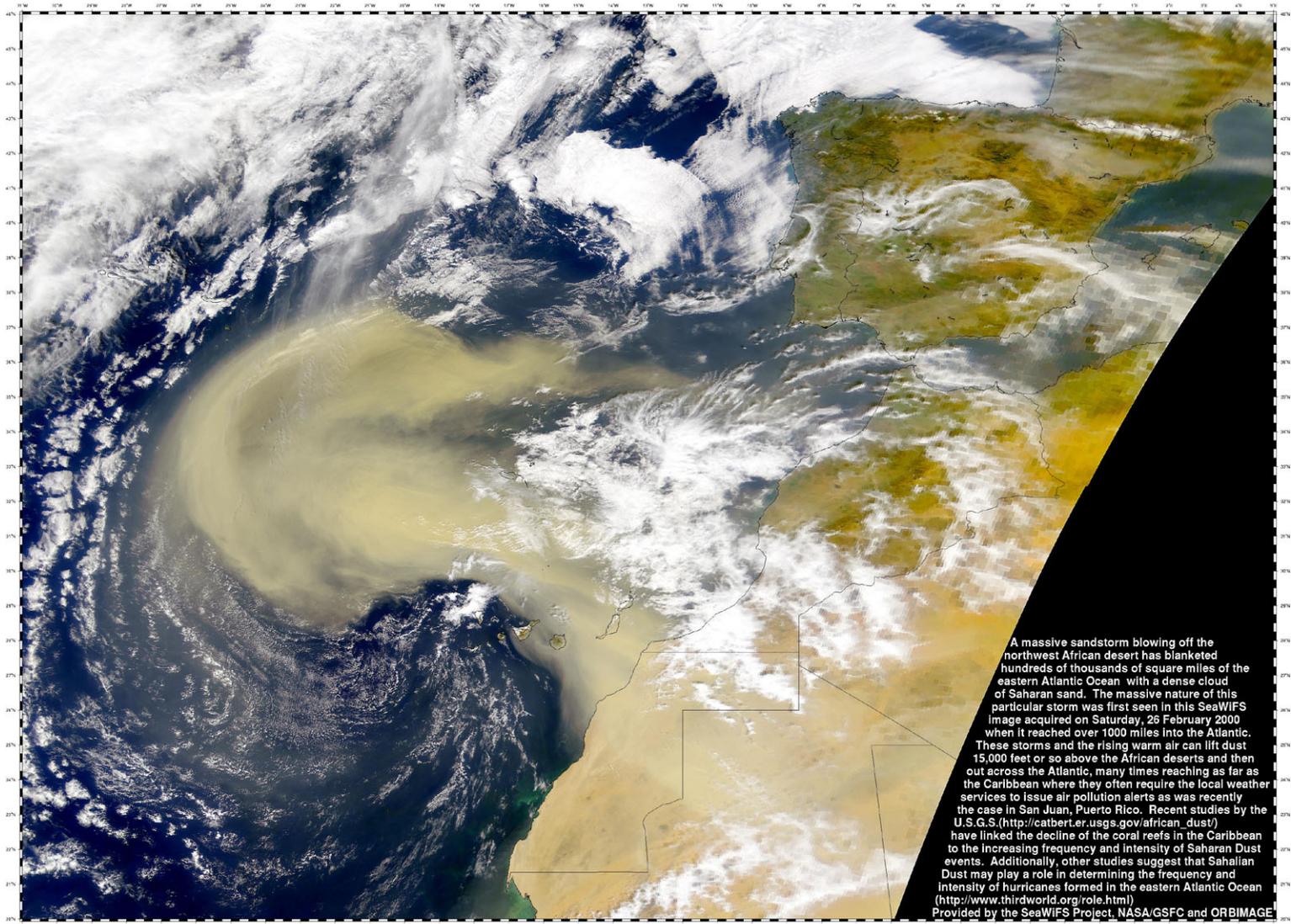
Change in Low Cloud Amount (%/K)

Some Other Sources of Uncertainty

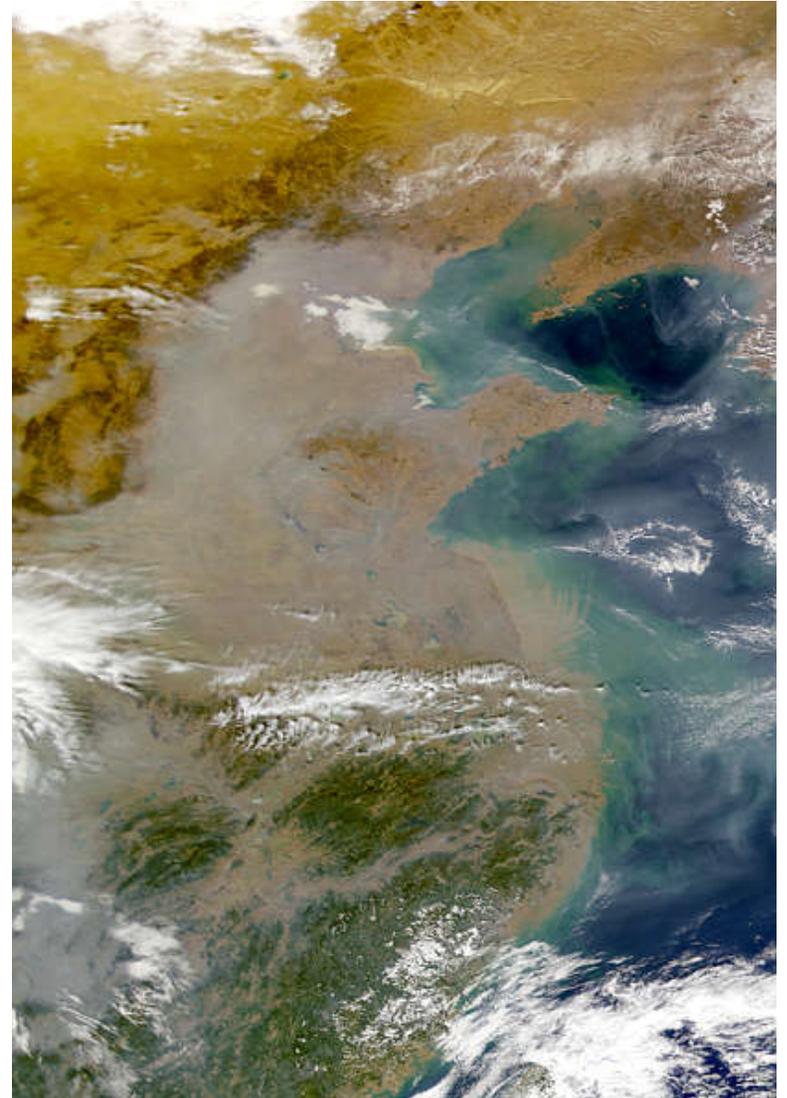
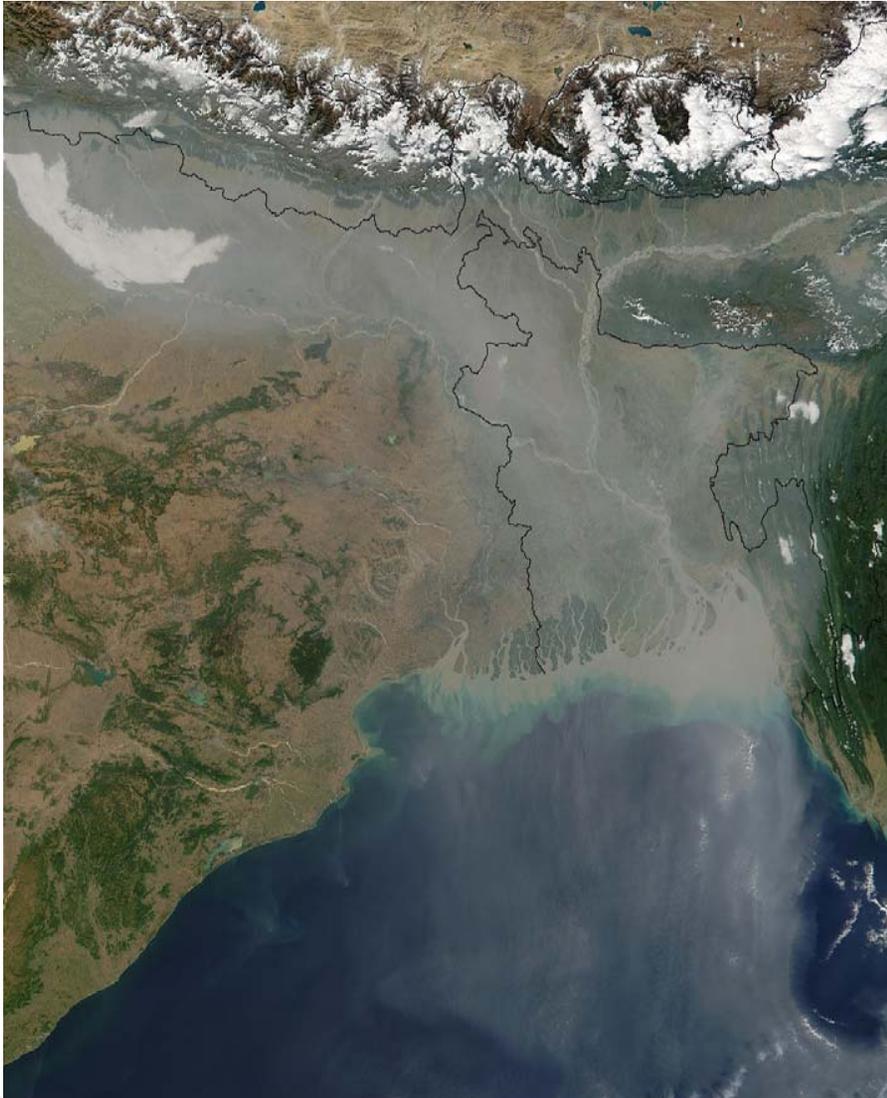


IPCC Working Group I (2001)

Energy Budget Impacts of Atmospheric Aerosol

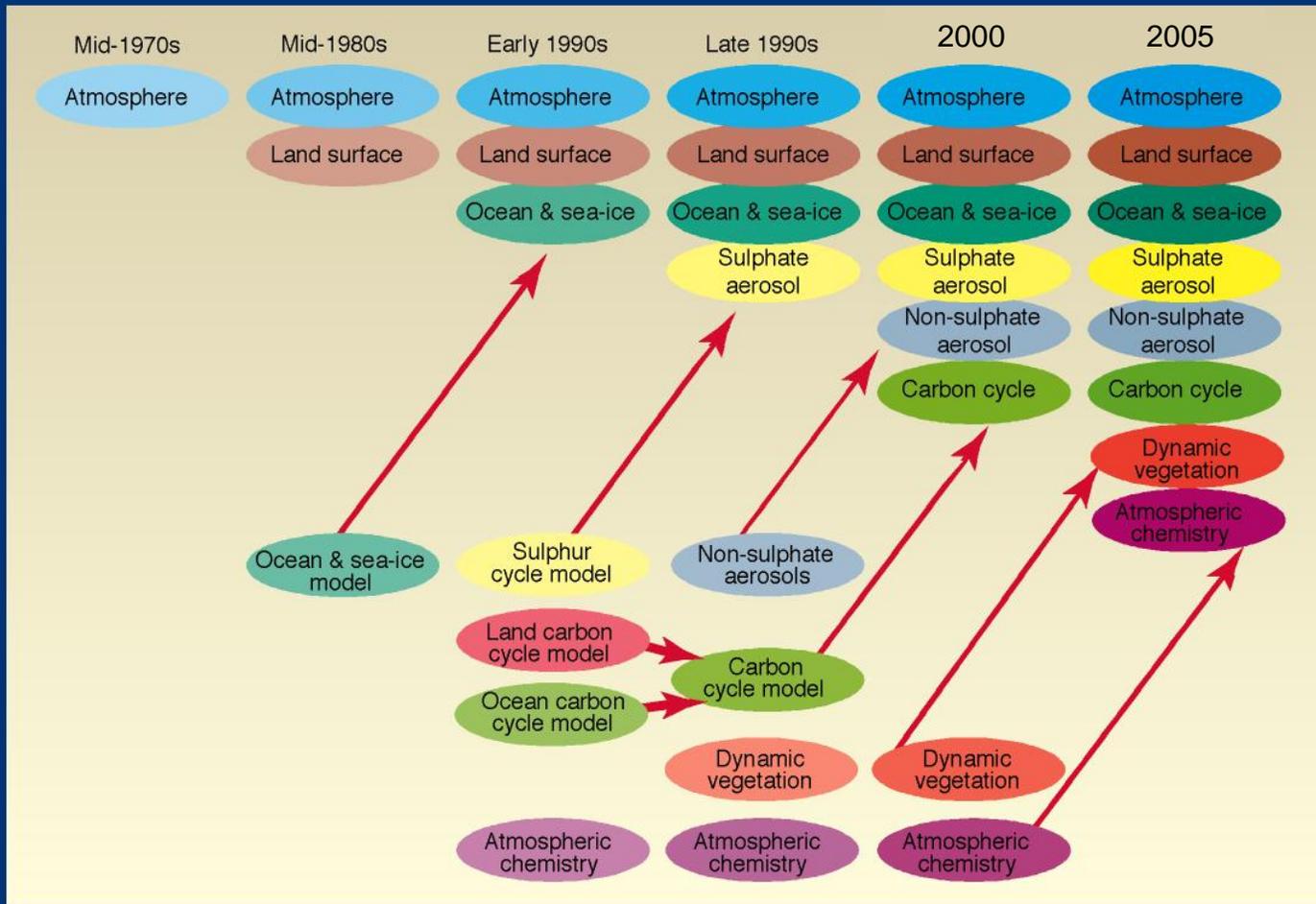


Energy Budget Impacts of Atmospheric Aerosol



Climate Model 'Evolution'

The development of climate models, past, present and future



WG1 - TS BOX 3
FIGURE 1

1x

3x

20x

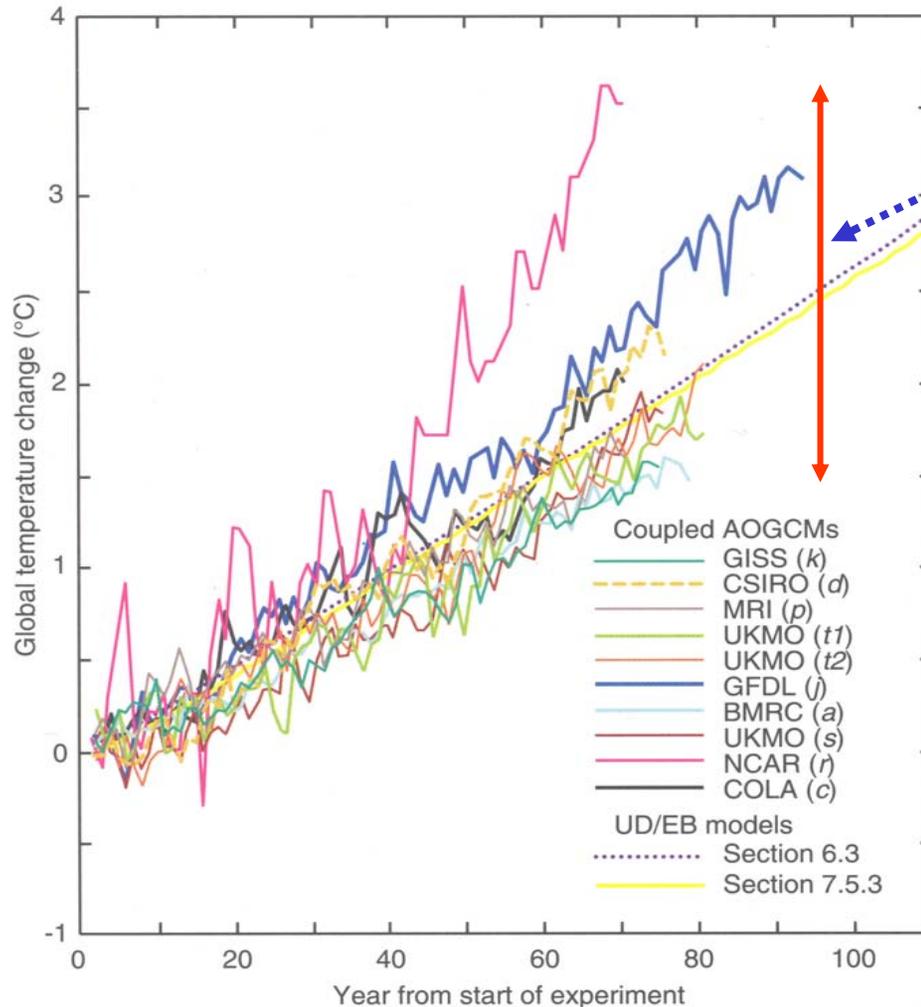
The Computational Efficiency Challenge

- 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

SciDAC has been central to tackling these challenges and will become even more important in the future!

Participation in Community Exercises

IPCC 1995: Climate Model Projections



Uncertainty presents scientific and credibility problem

Has not changed much in last decade

Extension of physical climate system may exacerbate uncertainty

Summary

- Global Climate Modeling
 - complex and evolving scientific problem
 - *climate science is not a solved problem!*
 - parameterization of physical processes is pacing progress
 - *this is not necessarily a well posed problem*
 - observational limitations are pacing process understanding
 - *this has ALWAYS been an important rate-limiting component*
 - computational limitations pacing exploration of model formulations
 - explorations of resolution parameter space, process modeling, system sensitivities, model validation (e.g., reproduce paleo record)
- Time for more comprehensive exploration of “spectral gap?”
 - ultra-high resolution simulations ($\sim 10^7x$)
 - super-parameterization (MMF) approach ($\sim 200x-500x$)

The End