Climate Simulation for Climate Change Studies

Workshop on Frontiers of Extreme Computing Santa Cruz, CA

October 27, 2005

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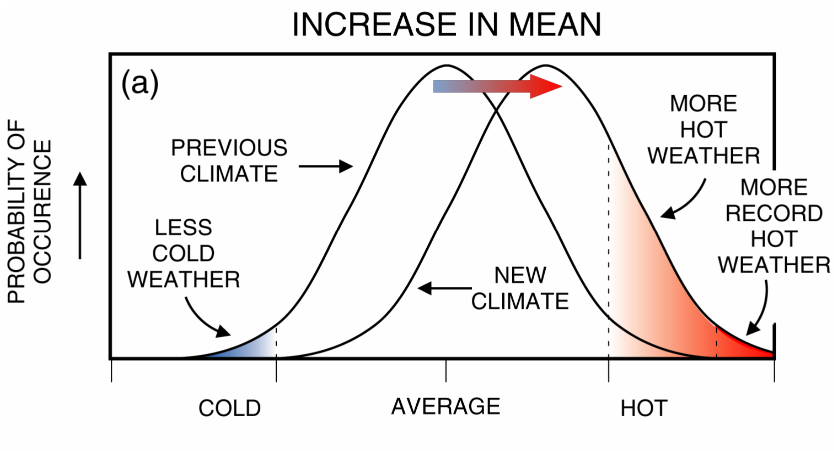
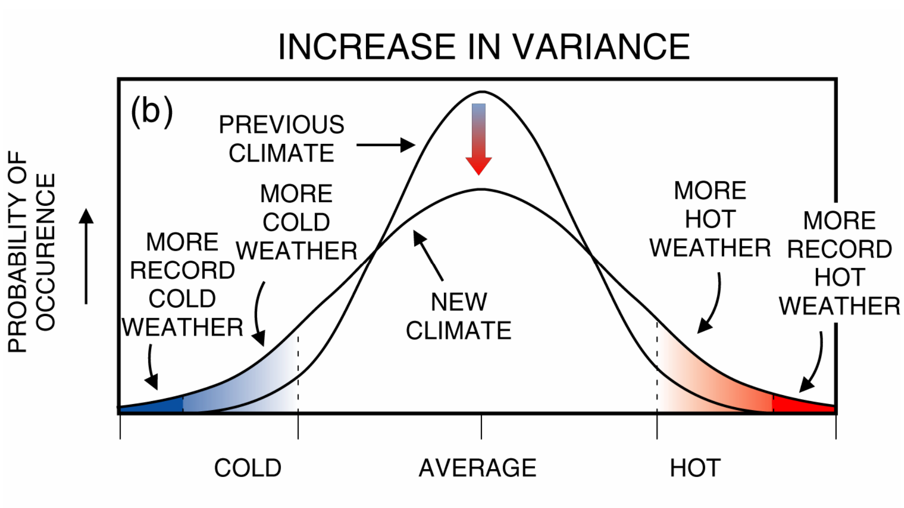
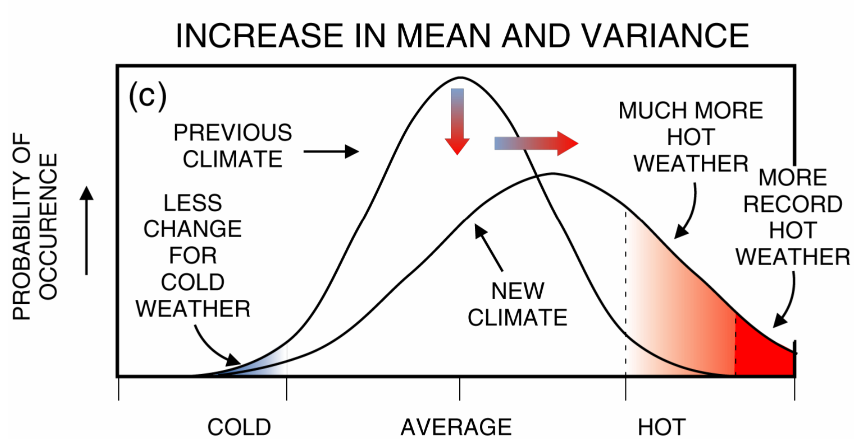
Climate-Change Science
Grand Challenge

Predict future climates based on scenarios of anthropogenic emissions and other changes resulting from options in energy policies



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





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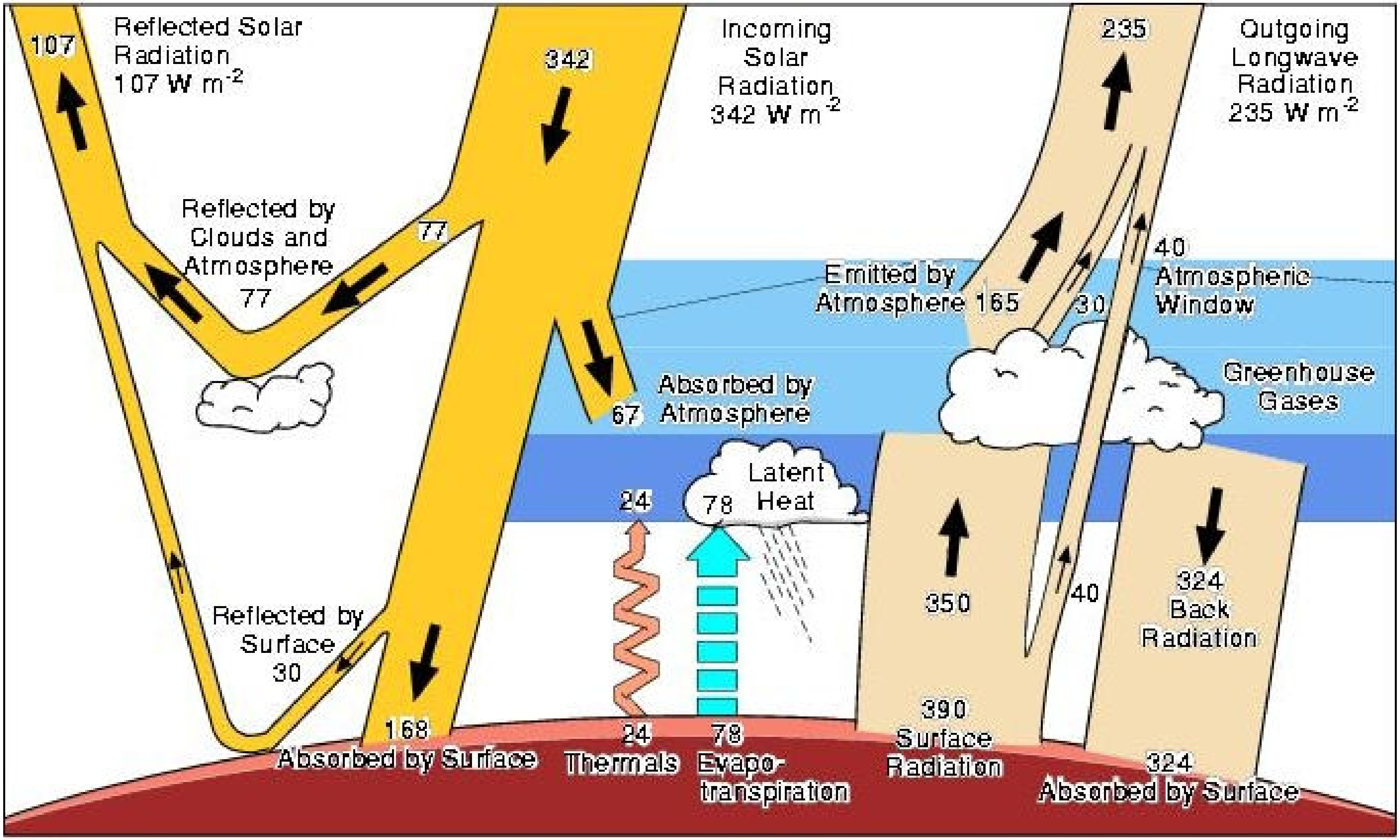
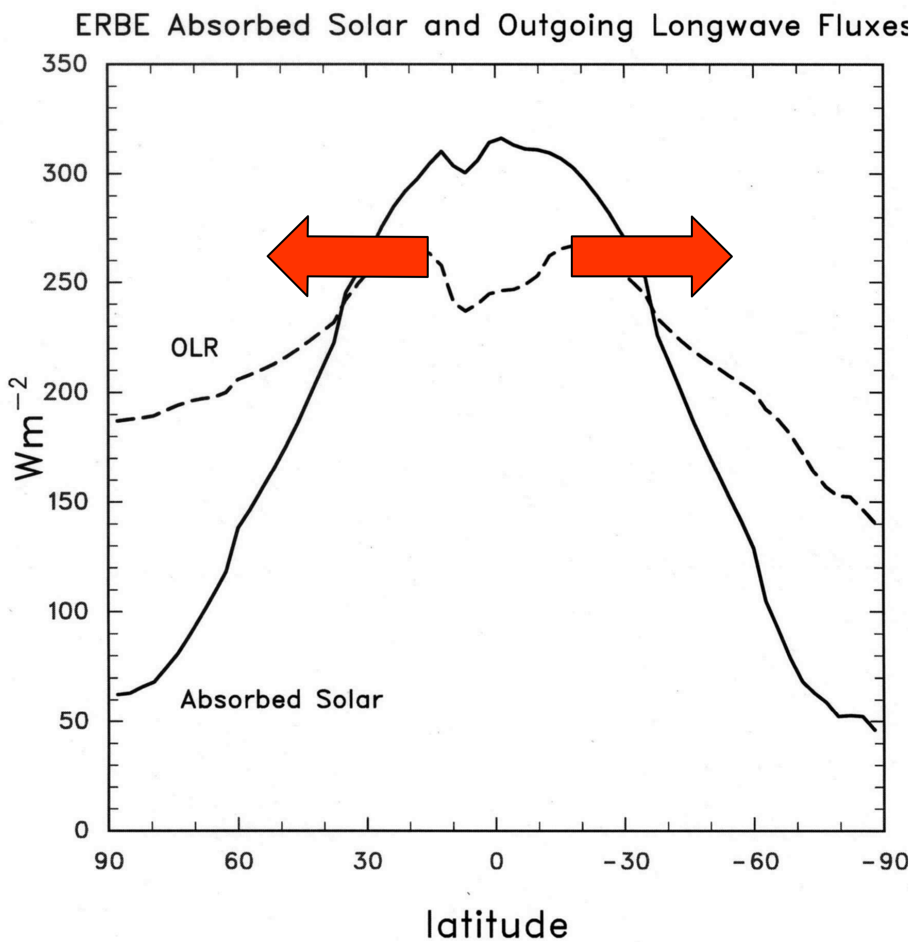
Global Heat Flows



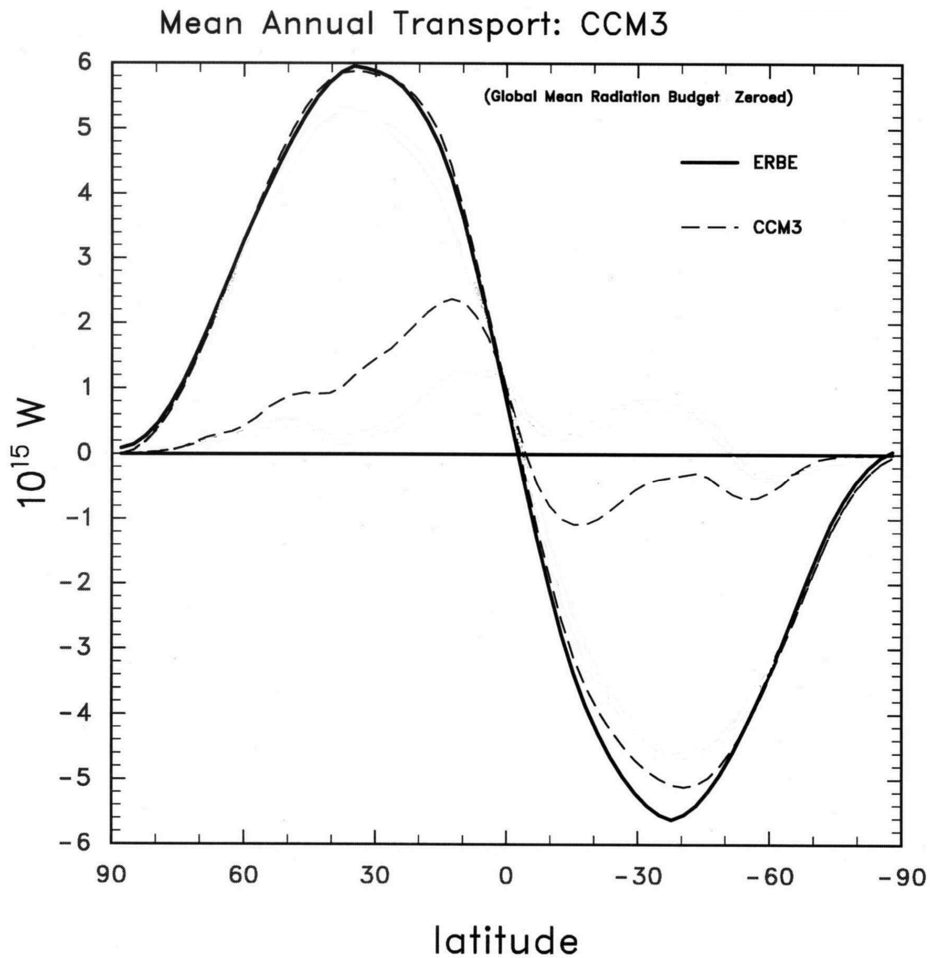
Kiehl and Trenberth 1997

Energy Balance: Fundamental Driver of the Scientific Problem

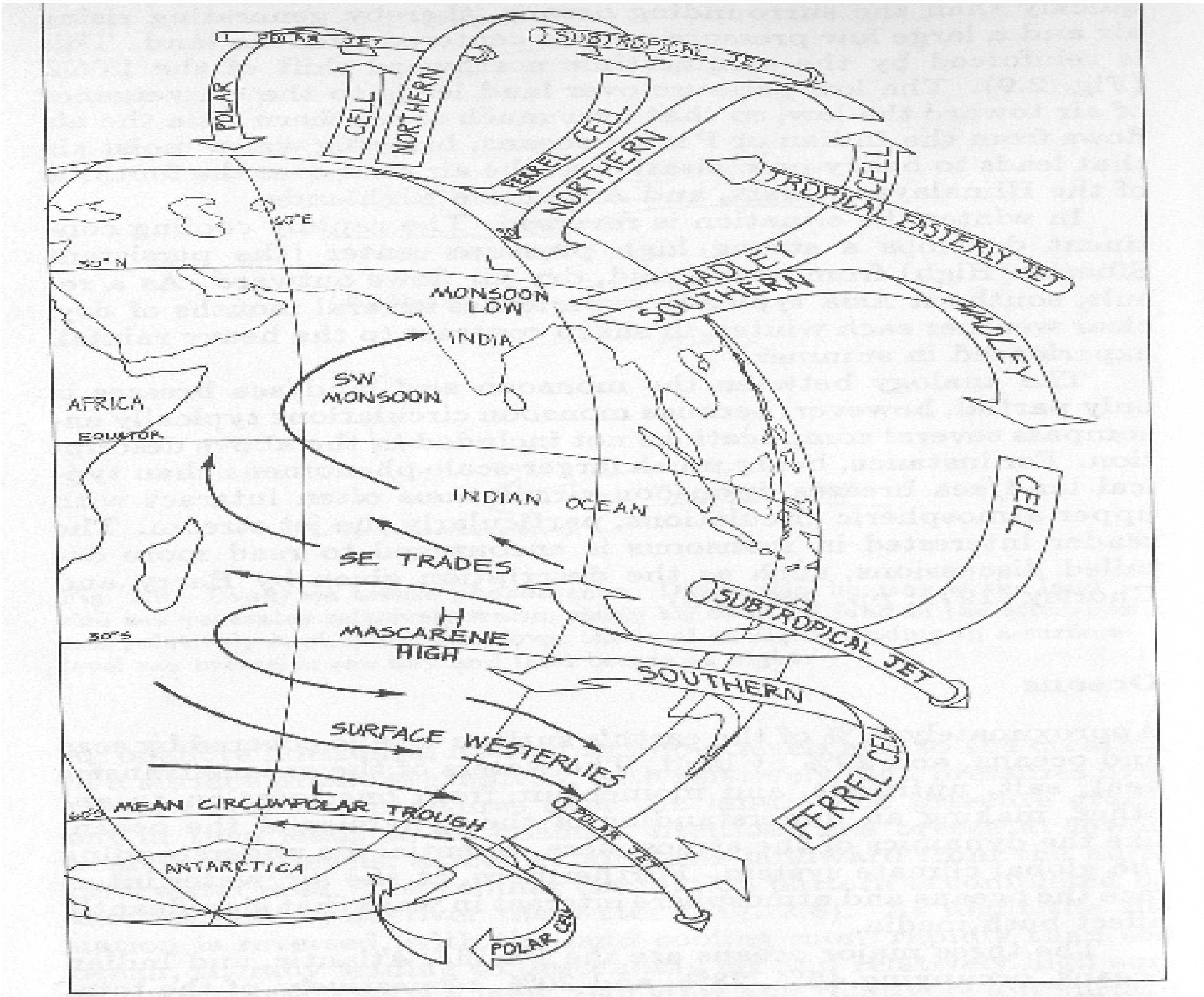
Longwave and Shortwave Energy Budget



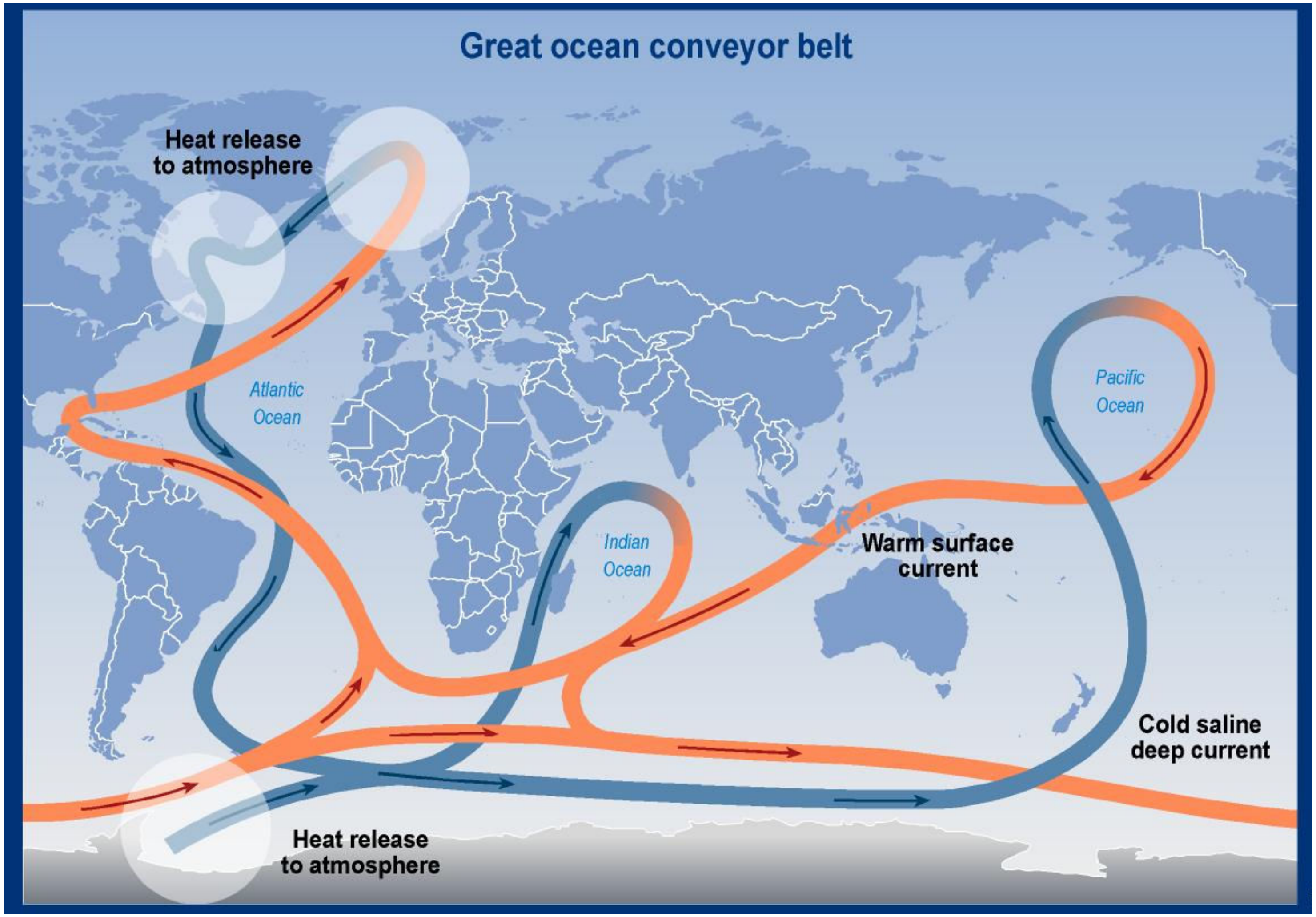
Northward Energy Transport



Three Cell Atmospheric General Circulation



Source: Washington and Parkinson



Source: IPCC 2001

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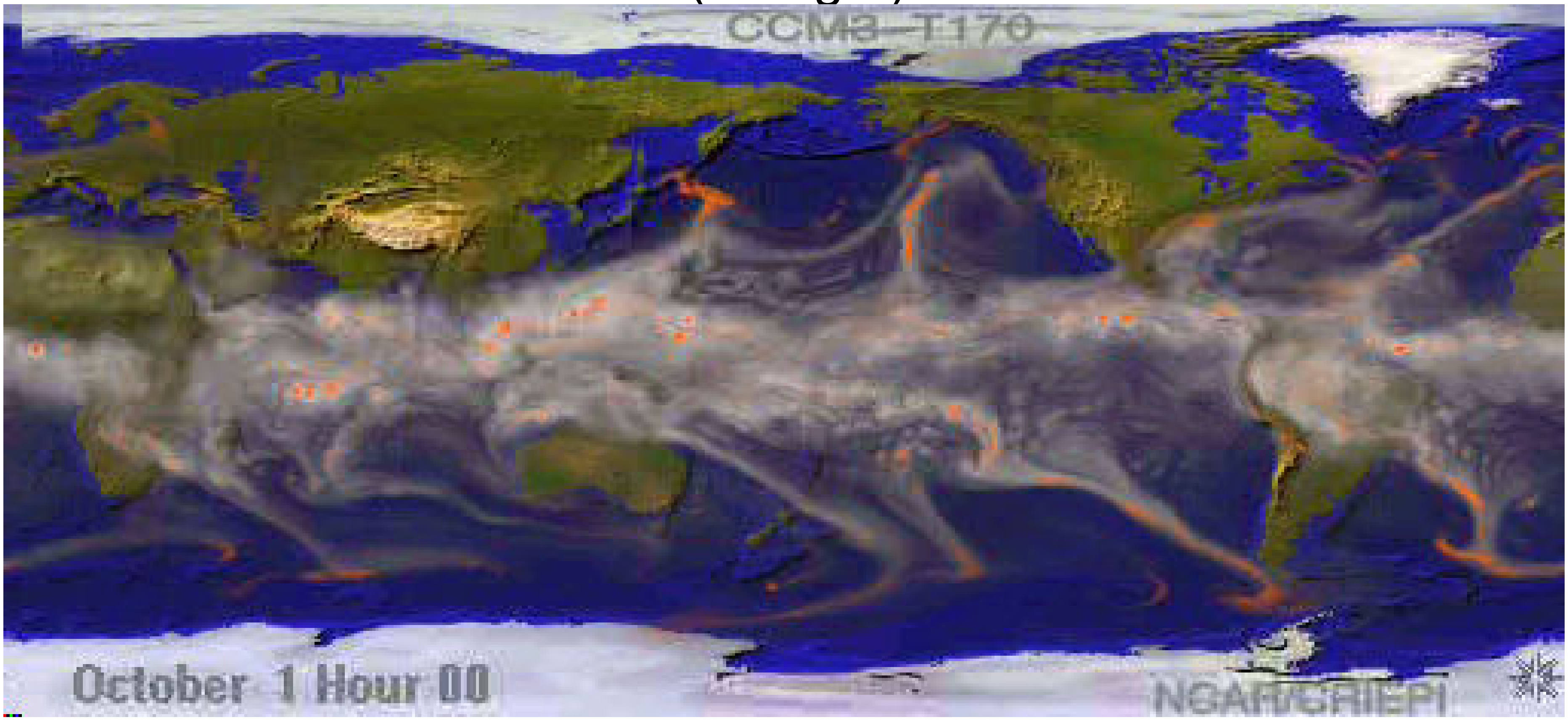
Example of Global Climate Model Simulation

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



Animation courtesy of NCAR SCD Visualization and Enabling Technologies Section

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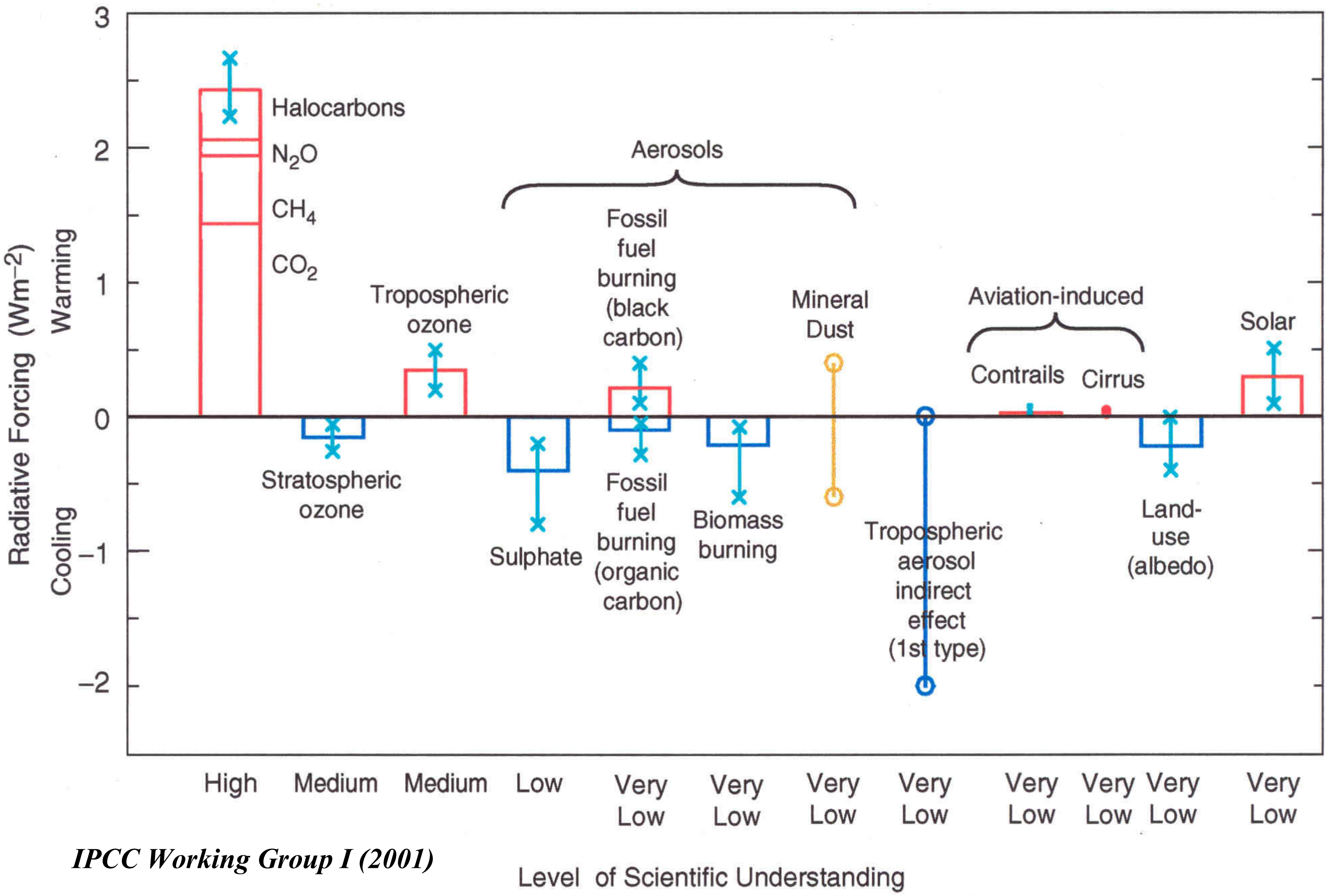
Change in Forcing 2000 vs 1750



IPCC Working Group I (2001)

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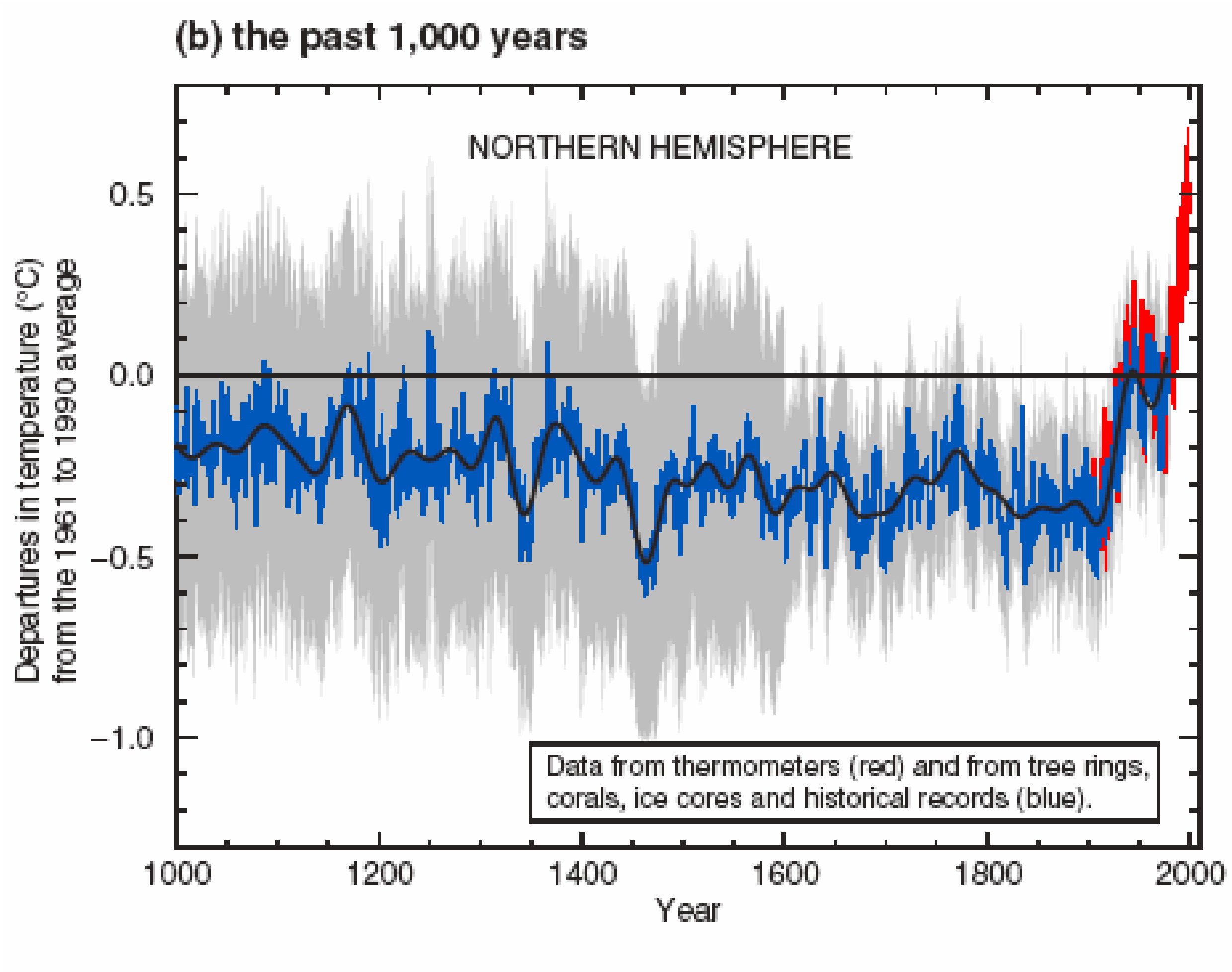
Observed Temperature Records



IPCC, 3rd Assessment, Summary For Policymakers

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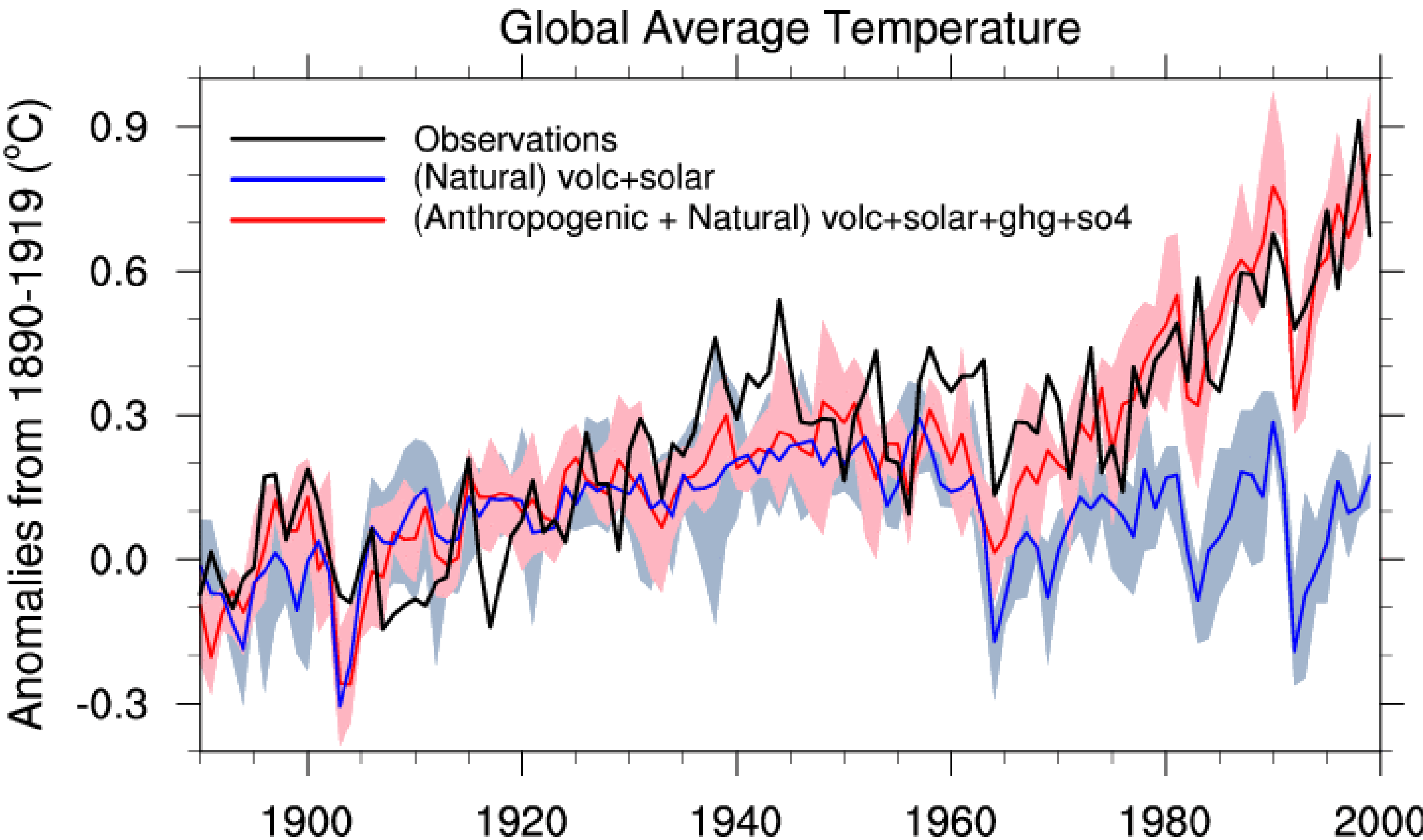
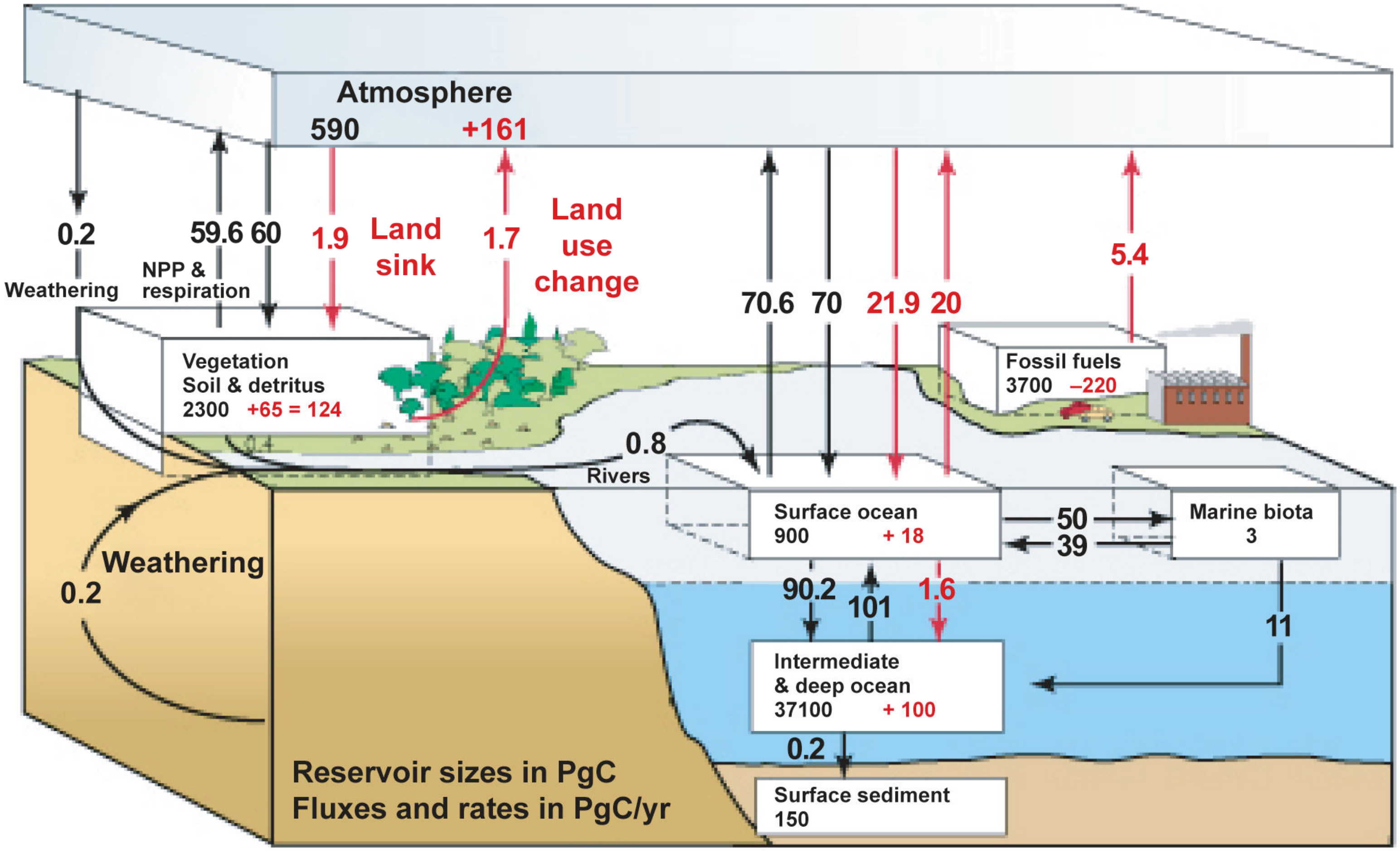
Observations: 20th Century Warming

Model Solutions with Human Forcing

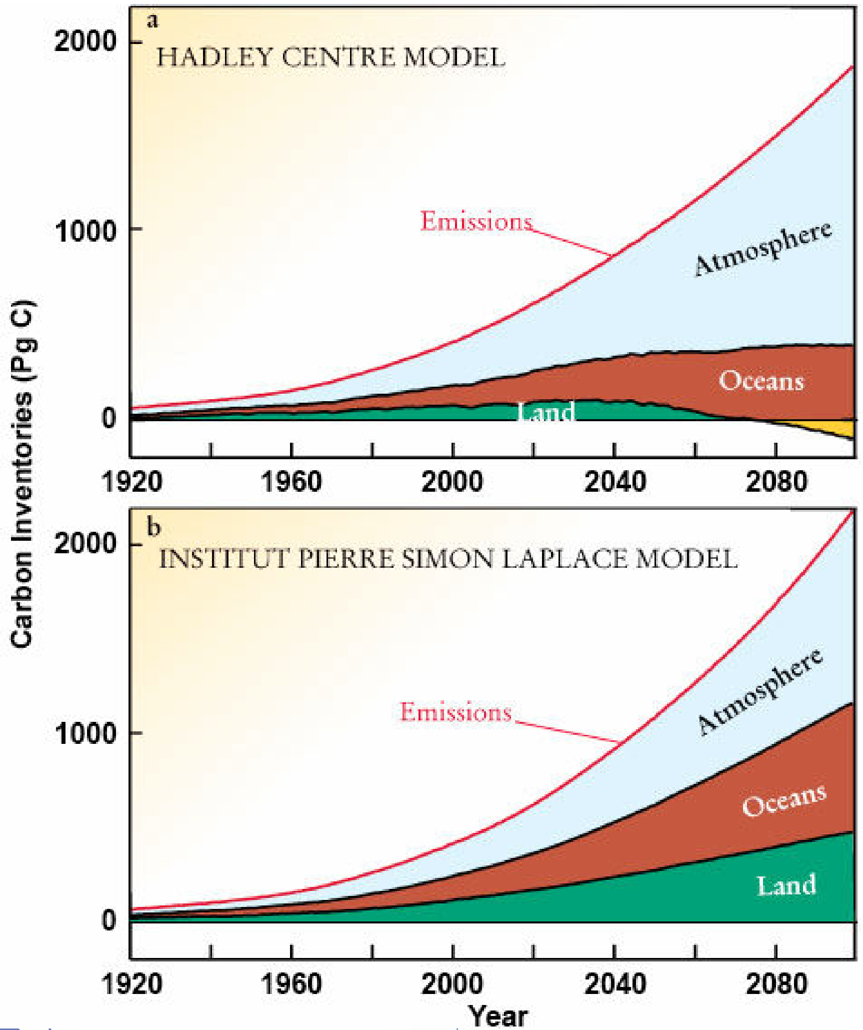


The carbon cycle is the next challenge



“The results are as uncertain as they are disconcerting”

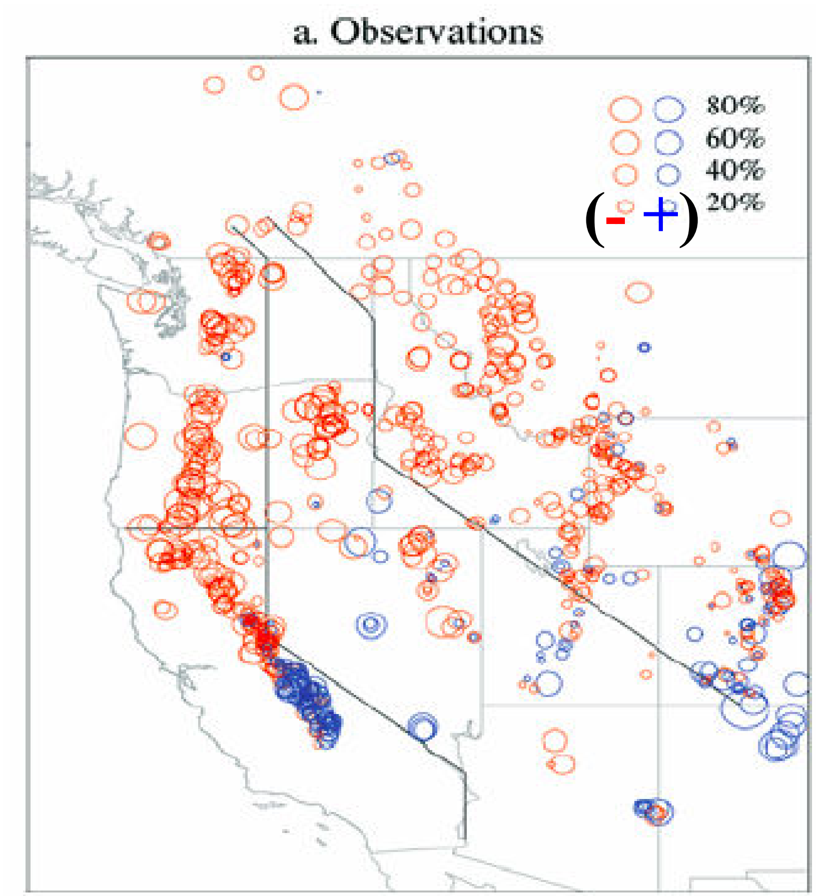
Jorge L. Sarmiento and Nicolas Gruber, “Sinks for Anthropogenic Carbon,” ***Physics Today***, August 2002



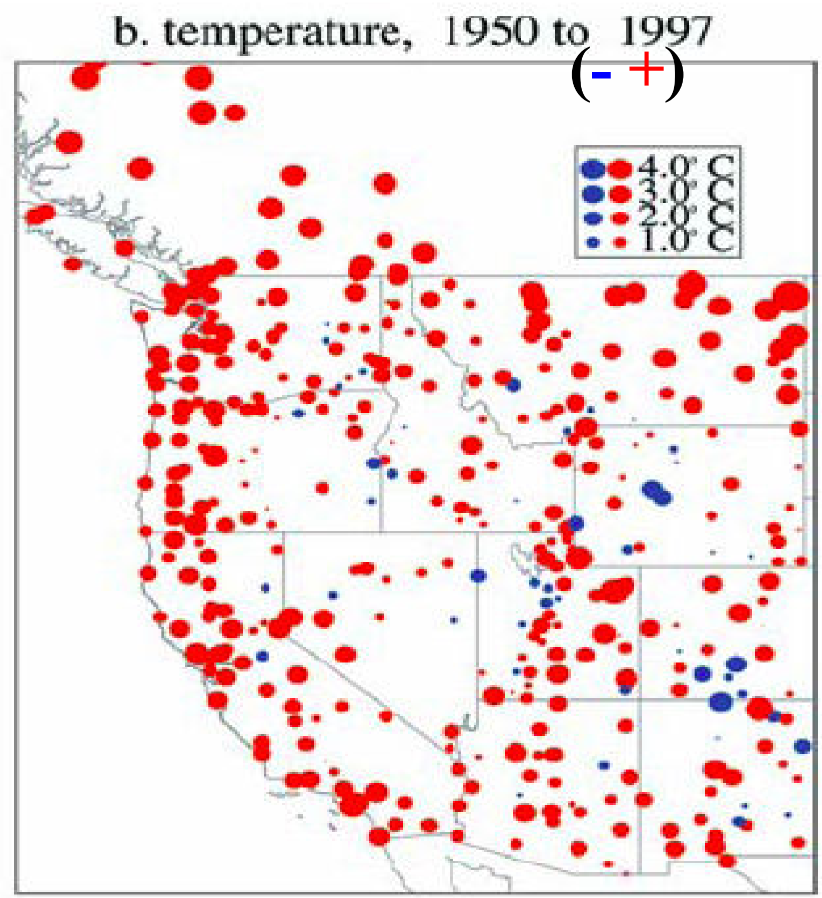
Impacts of Climate Change

Observed Change 1950-1997

Snowpack



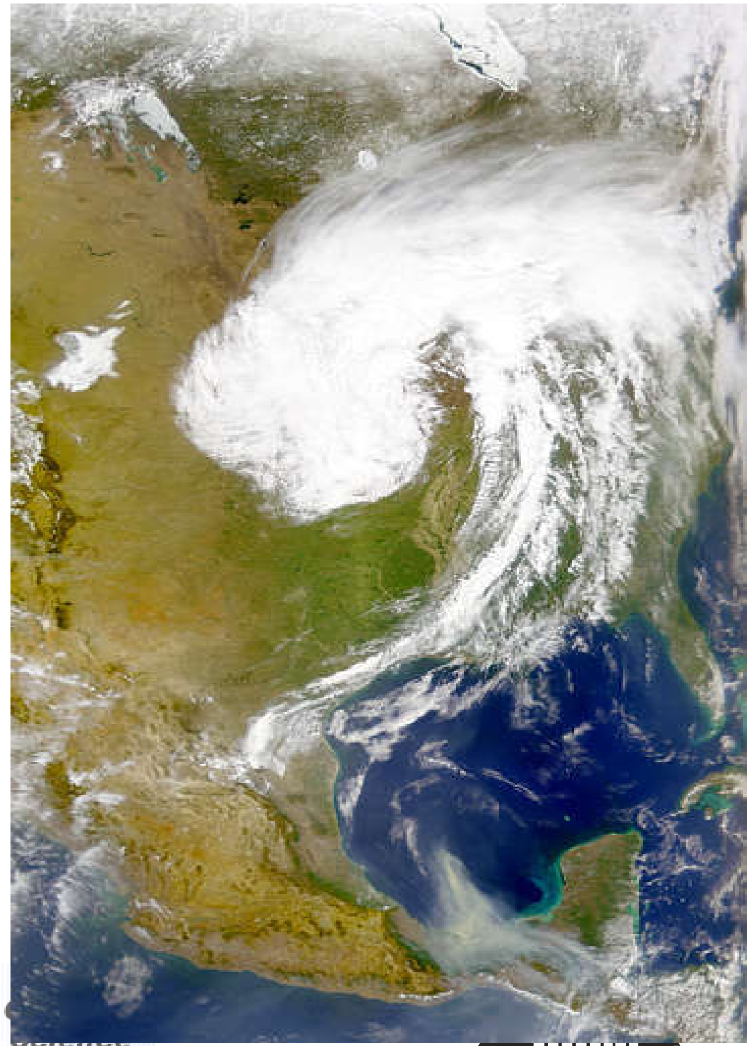
Temperature



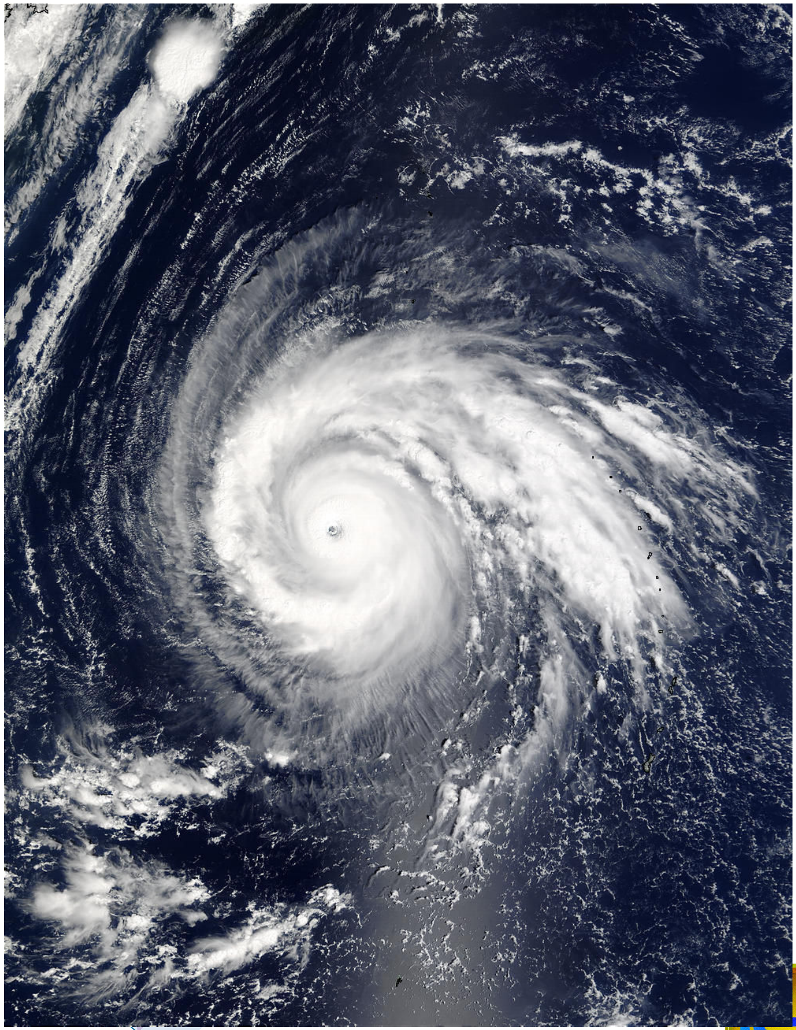
Under-resolved Processes

Synoptic-scale mechanisms and clouds

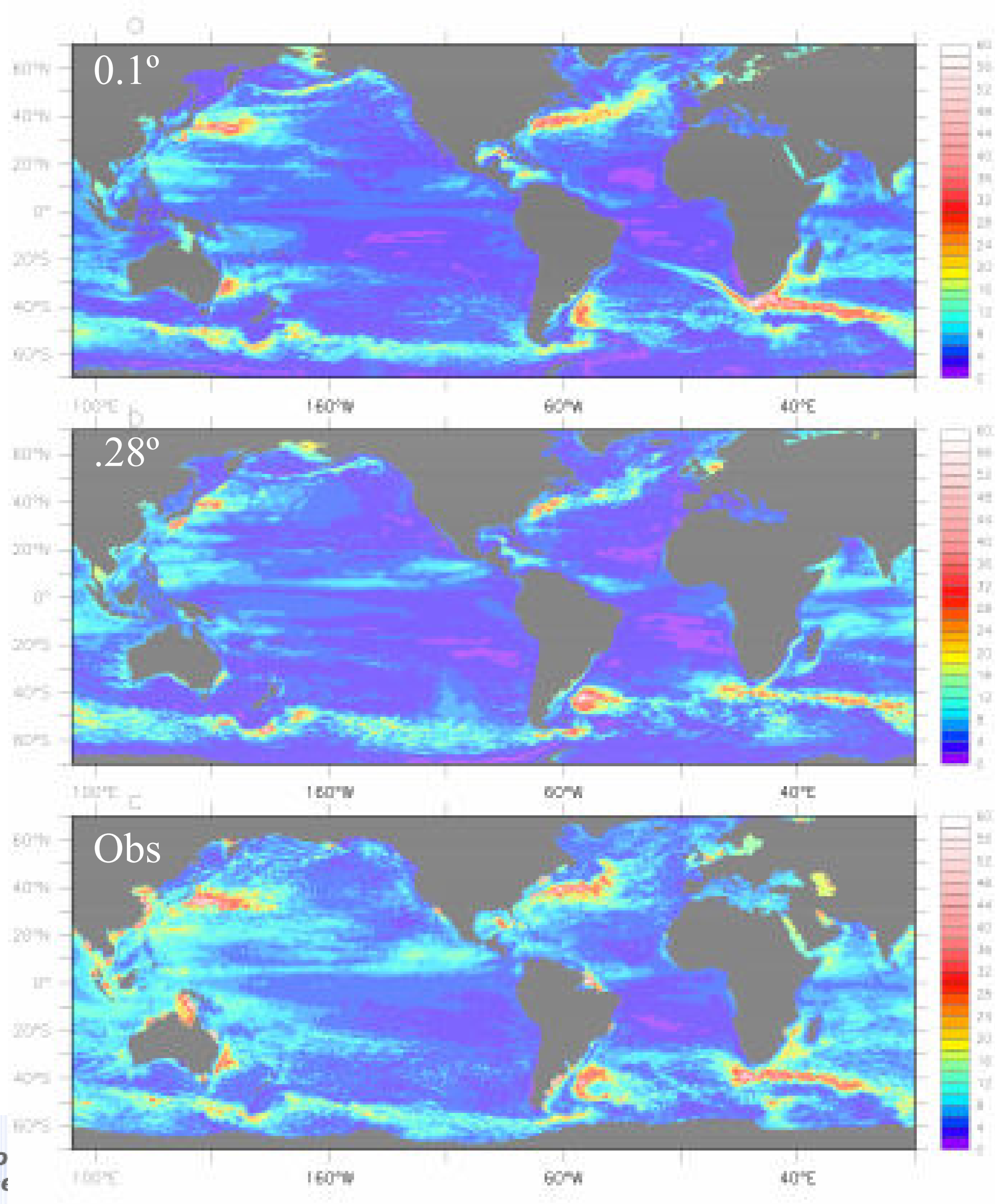
• extratropical storms



• hurricanes



http://www.earth.nasa.gov

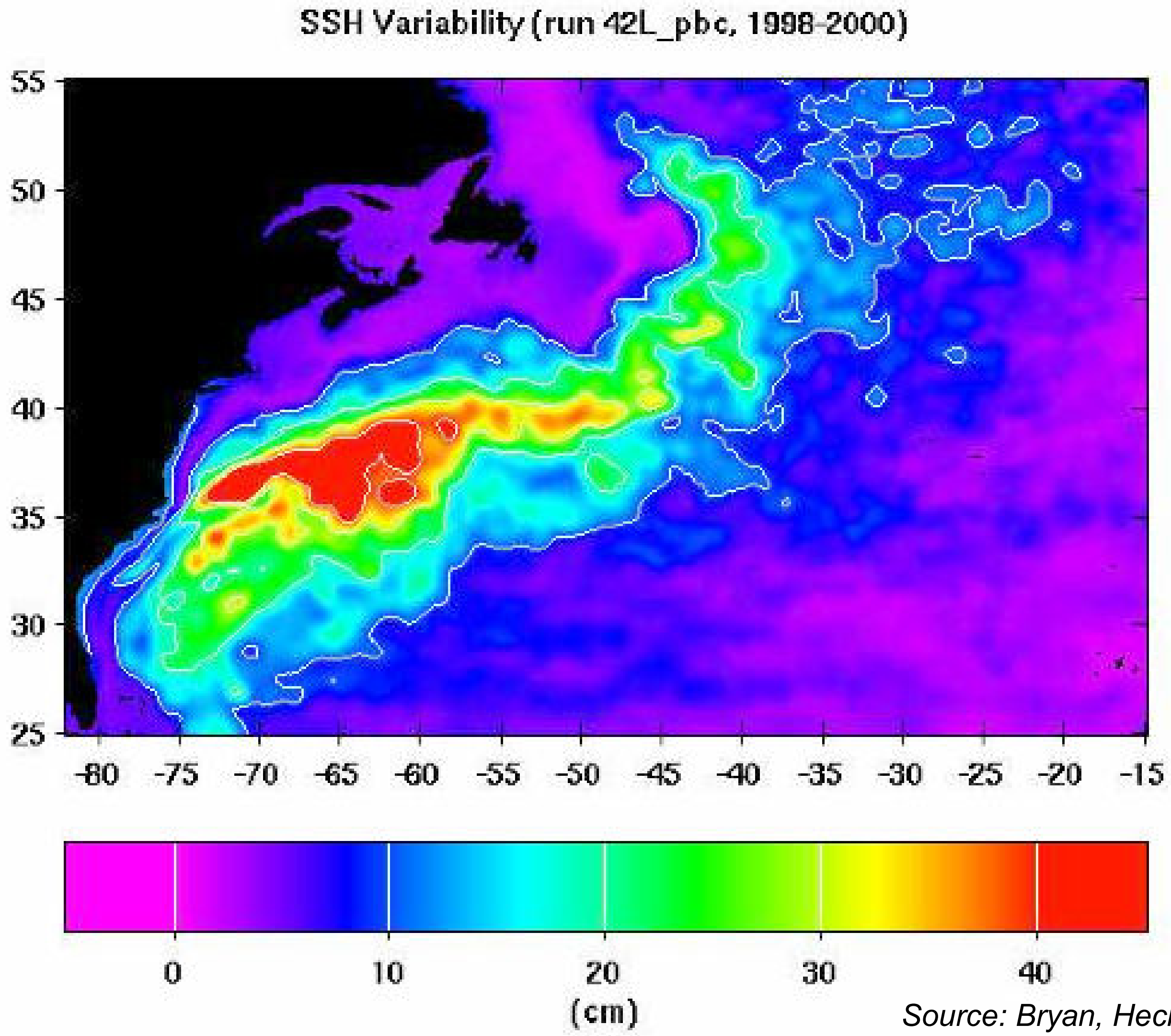


Errors and biases:

North Atlantic Current **does not** reach NW corner

Source: Maltrud and McClean, 2004

Good NW Corner with Partial Bottom Cells



Source: Bryan, Hecht, and Smith

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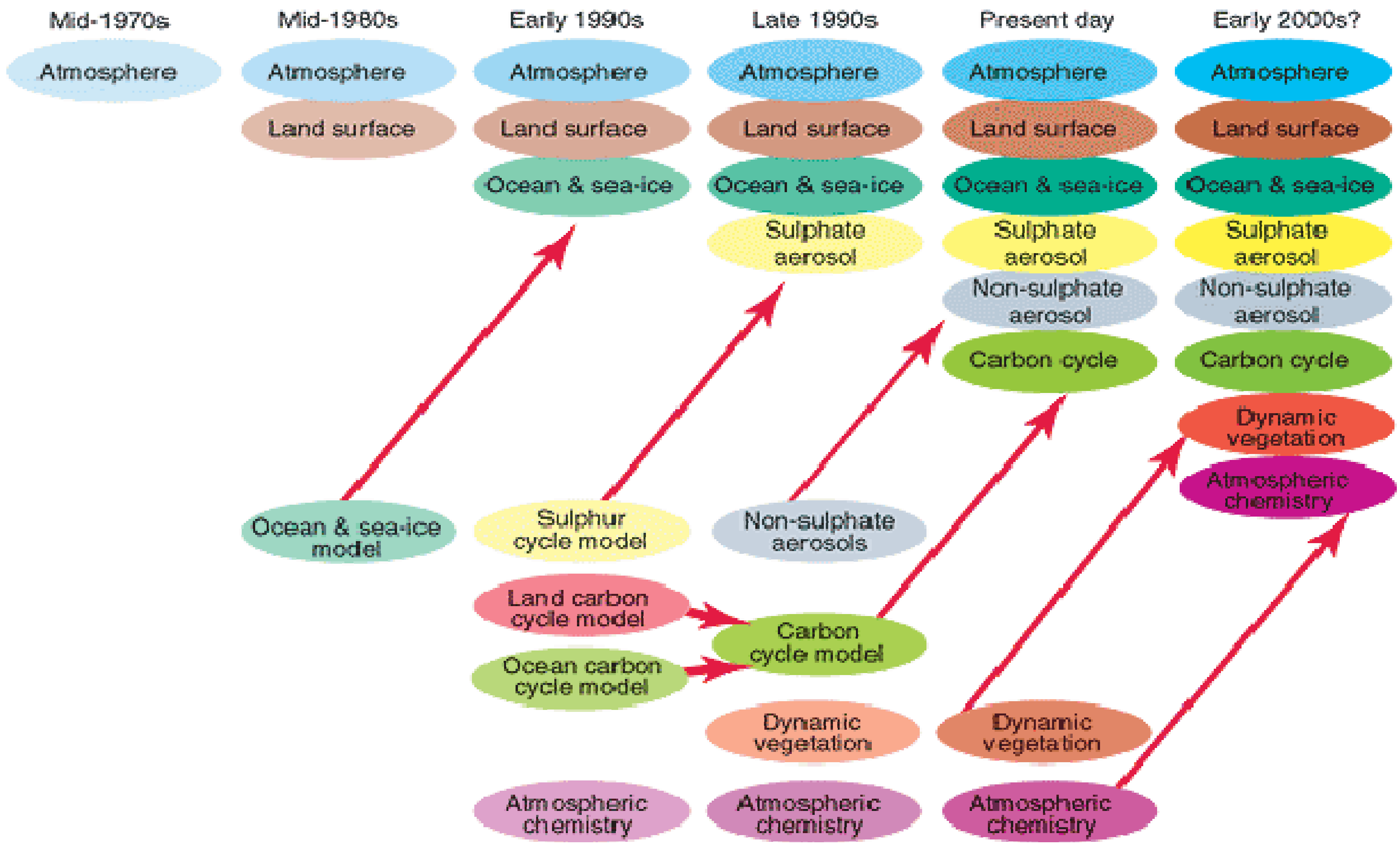
The Development of Climate models, Past, Present and Future



Source: IPCC 2001

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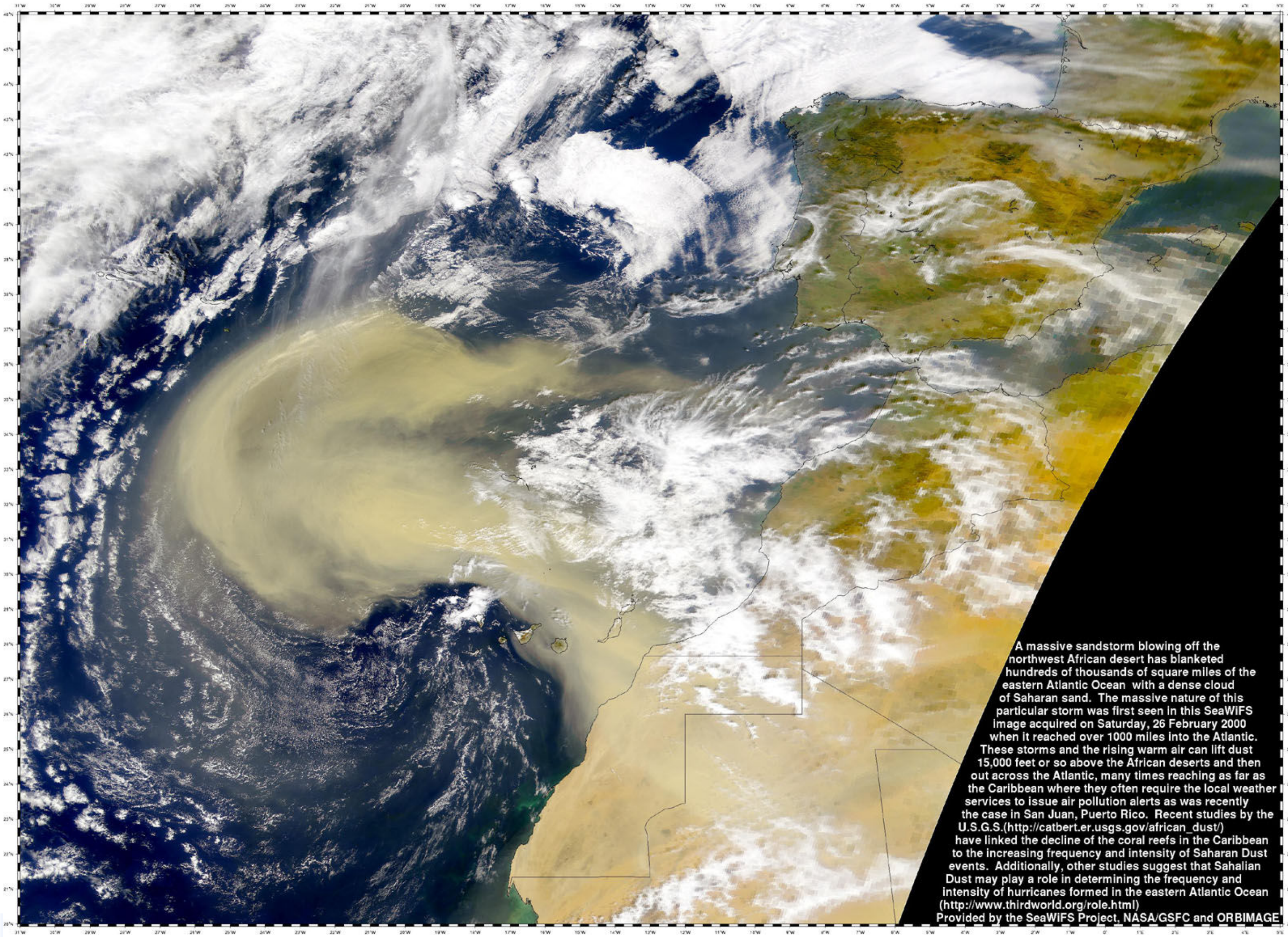
A sample budget for computing needs for CCSM4

Process	Number	Cost
Chemistry	94	400 – 500% (CAM)
Atmos. Res.→1°		× 5
Ocean BGC	25	250 – 375% (POP)
Land BGC	40	< 20% (CLM)
Total	159	> 20 – 25× ≅ Chem × Res.

The IPCC AR4 Required the Equivalent of a "Cheetah-year"(4.5 TFLOP IBM SP) → in five years need ~100 TFLOP Dedicated Machine for 1 Model

Unrepresented Processes:Atmospheric Aerosol



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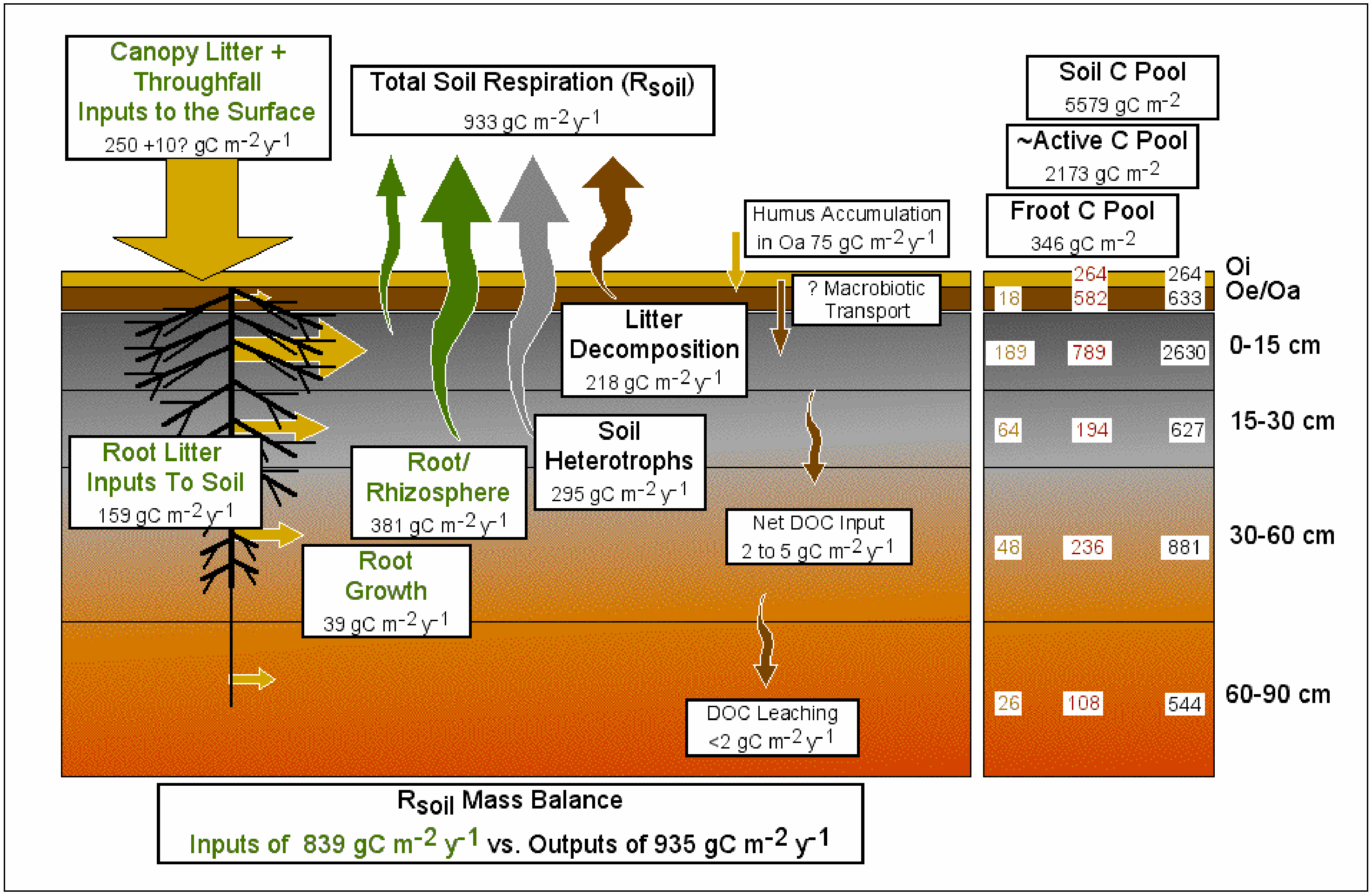
EBIS - Whole-system ^{14}C flux and storage characterization



Parameterization is Scale Selective

Moist Convection Example

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

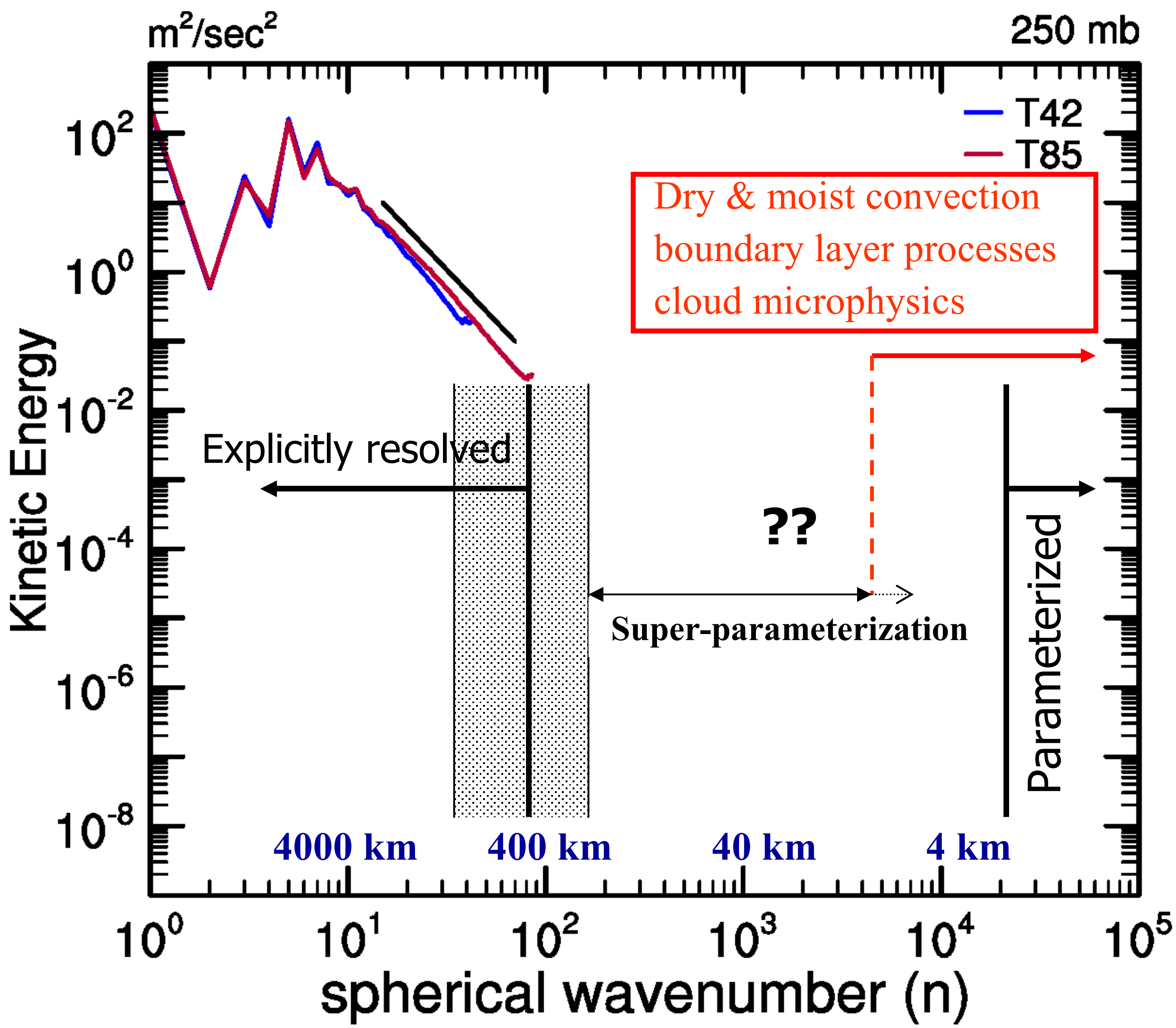
Moisture $$\frac{\partial \bar{q}}{\partial t} = -\nabla \cdot \bar{\mathbf{V}}\bar{q} - \frac{\partial \bar{\omega}\bar{q}}{\partial p} - \frac{\partial}{\partial p}(\overline{\omega'(q' + l')}) - \Re$$

we resolve the “large scale”

and parameterize the unresolved scales

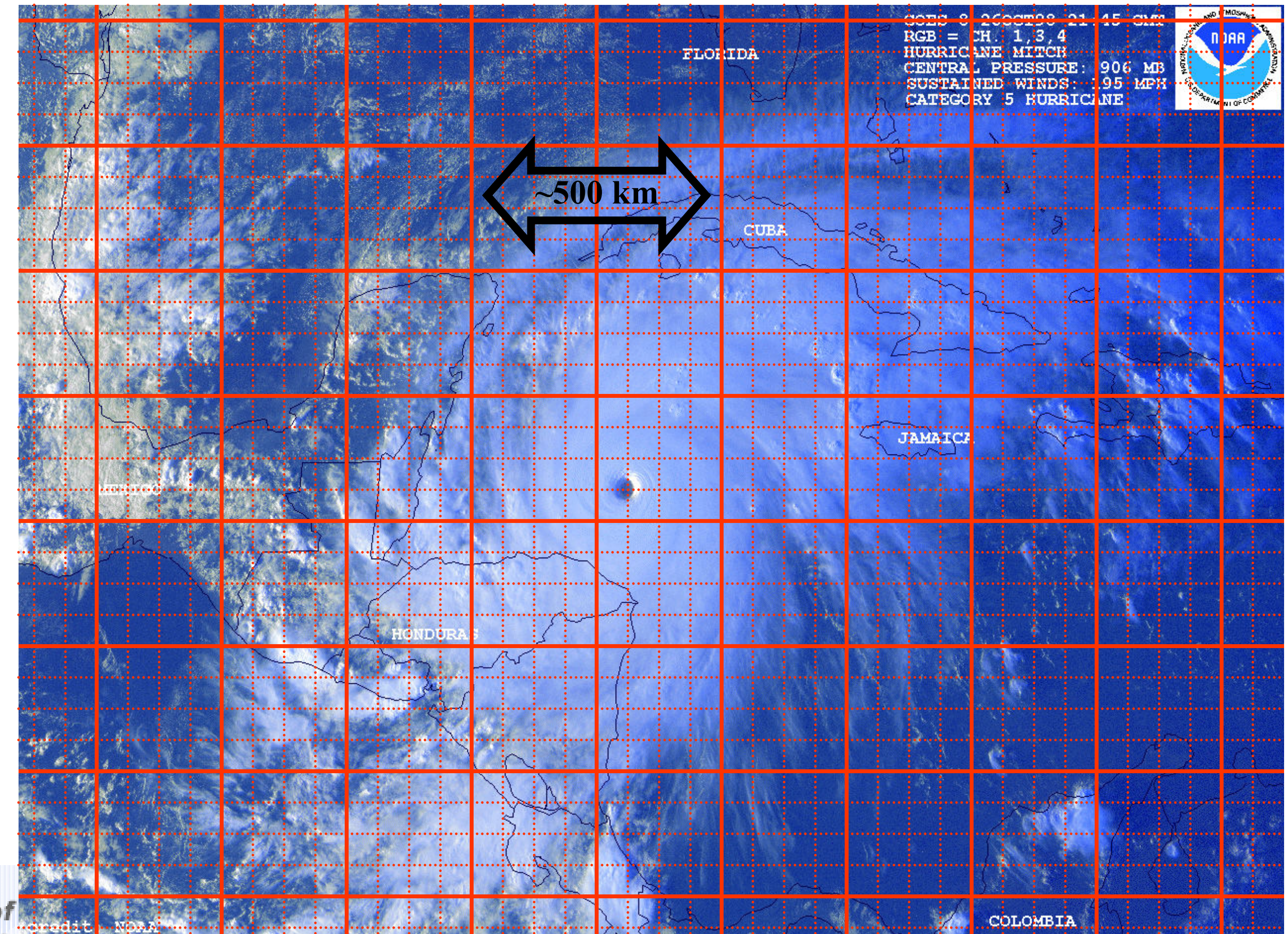
What happens to the “large-scale” motions seen by the parameterized physics as resolution is changed?

Atmospheric Motion Scales and Parameterization

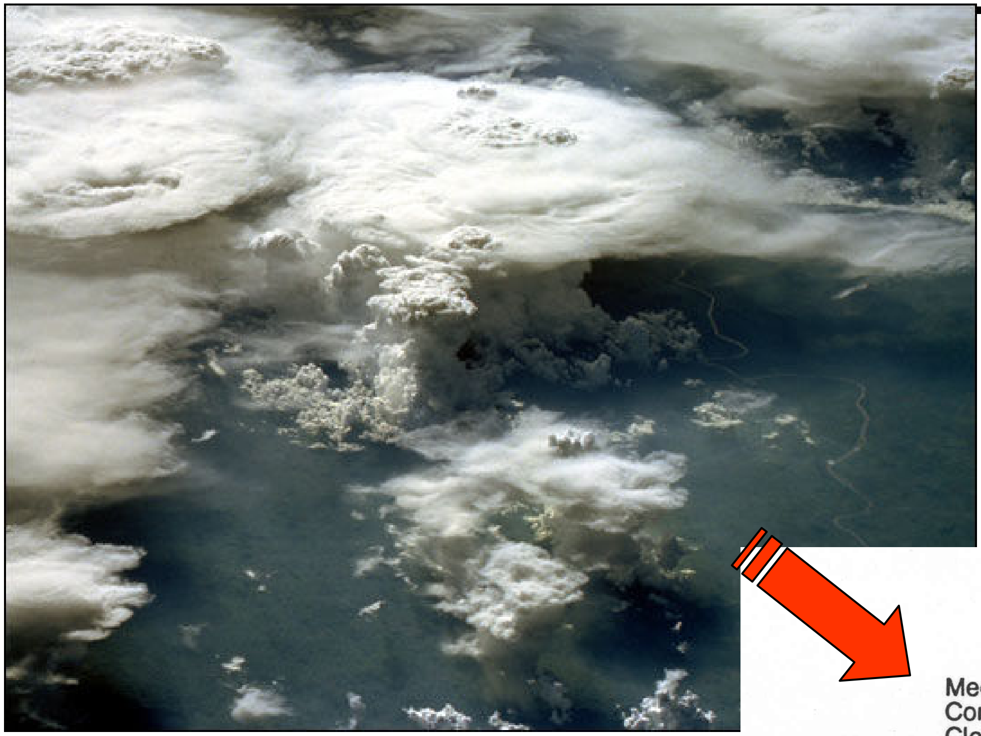


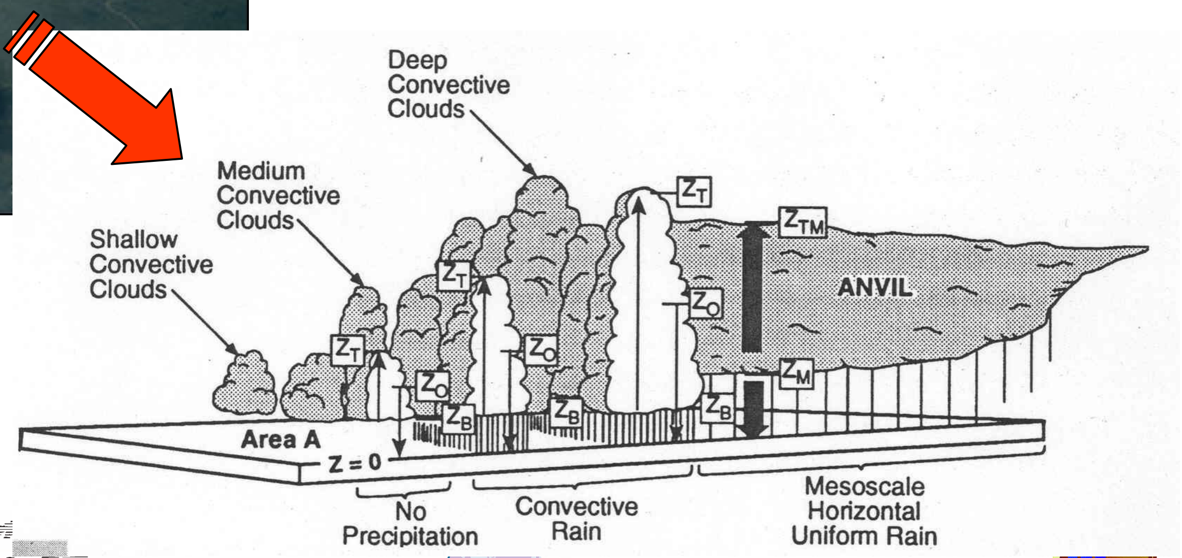
T42(2000) ***vs T170***(2005)

Better Simulation of Tropical Cyclone Impacts on Climate



Process Models and Parameterization





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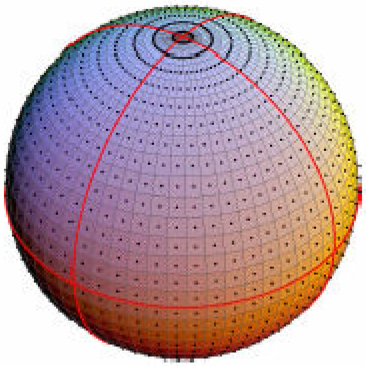
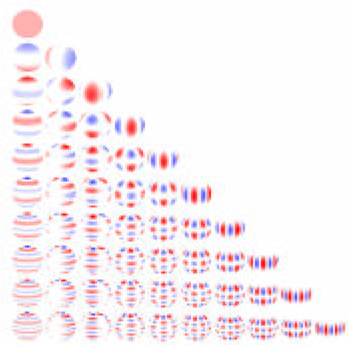
Time for more comprehensive exploration of "spectral gap?"

- ultra-high resolution simulations (~10^7x)
- super-parameterization (MMF) approach (~200x-500x)

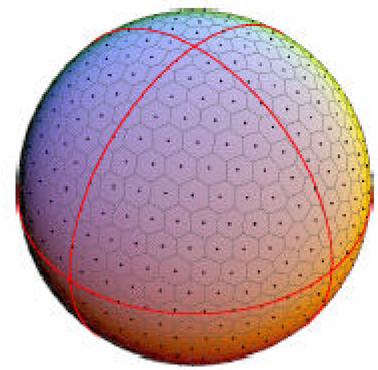
Horizontal discretization



Lat-lon



Spectral



Geodesic

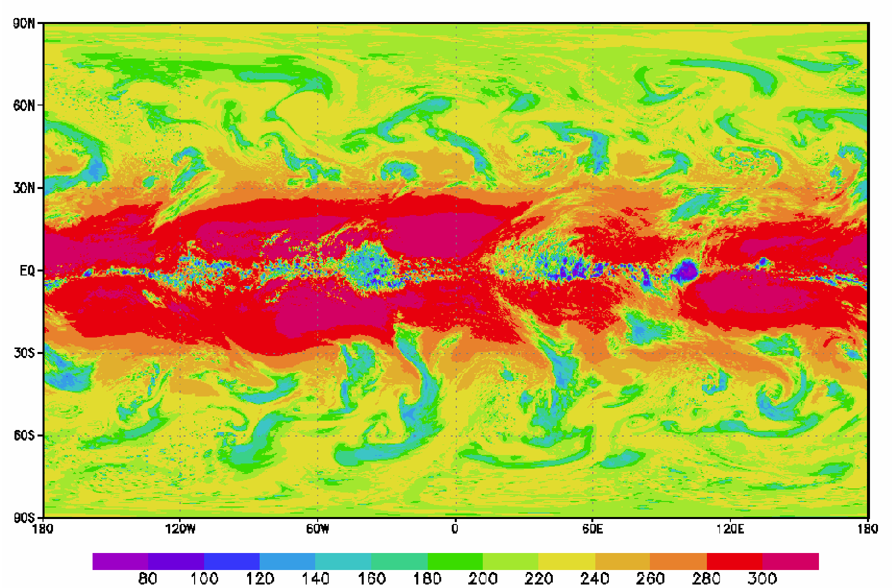
	Pluses	Minuses
Lat-lon		Pole problem
Spectral	No pole problem	Gibbs phenomenon
Geodesic	Homogeneous, isotropic grid	

GFDL	Spectral->Lat-lon
NCAR	Spectral (-> Lat-lon?)
GISS	Lat-lon
FRSGC	Geodesic
MPI	Spectral -> Geodesic

The World's First Global Cloud-Resolving Model

- Ocean-covered Earth
- 3.5 km cell size, ~10^7 columns
- 54 layers, ~10^9 total cells
- State ~ 1 TB
- Top at 40 km
- 15-second time step
- Spun up with coarser resolution
- 10 days of simulation
- ~10 simulated days per day on half of the Earth Simulator (2560 CPUs, 320 nodes), close to 10 real TF.

- 1 TF-year per simulated year



Computing Needs and Realities

- Throughput required ~5 years/day for ensemble simulation (century/month)
- 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*
- Quality of solutions are resolution and physics limited
  - balance horizontal and vertical resolution, and physics complexity
  - *computational capability 0th-order rate limiter*

Issue	*Motivation*	*Compute Factor*
Spatial resolution	Provide regional details	10^3-10^5
Model completeness	Add "new" science	10^2
New parameterizations	Upgrade to "better" science	10^2
Run length	Long-term implications	10^2
Ensembles, scenarios	Range of model variability	10
Total Compute Factor		10^{10}-10^{12}

Ref: ***A SCIENCE-BASED CASE FOR LARGE-SCALE SIMULATION***

Volume 2

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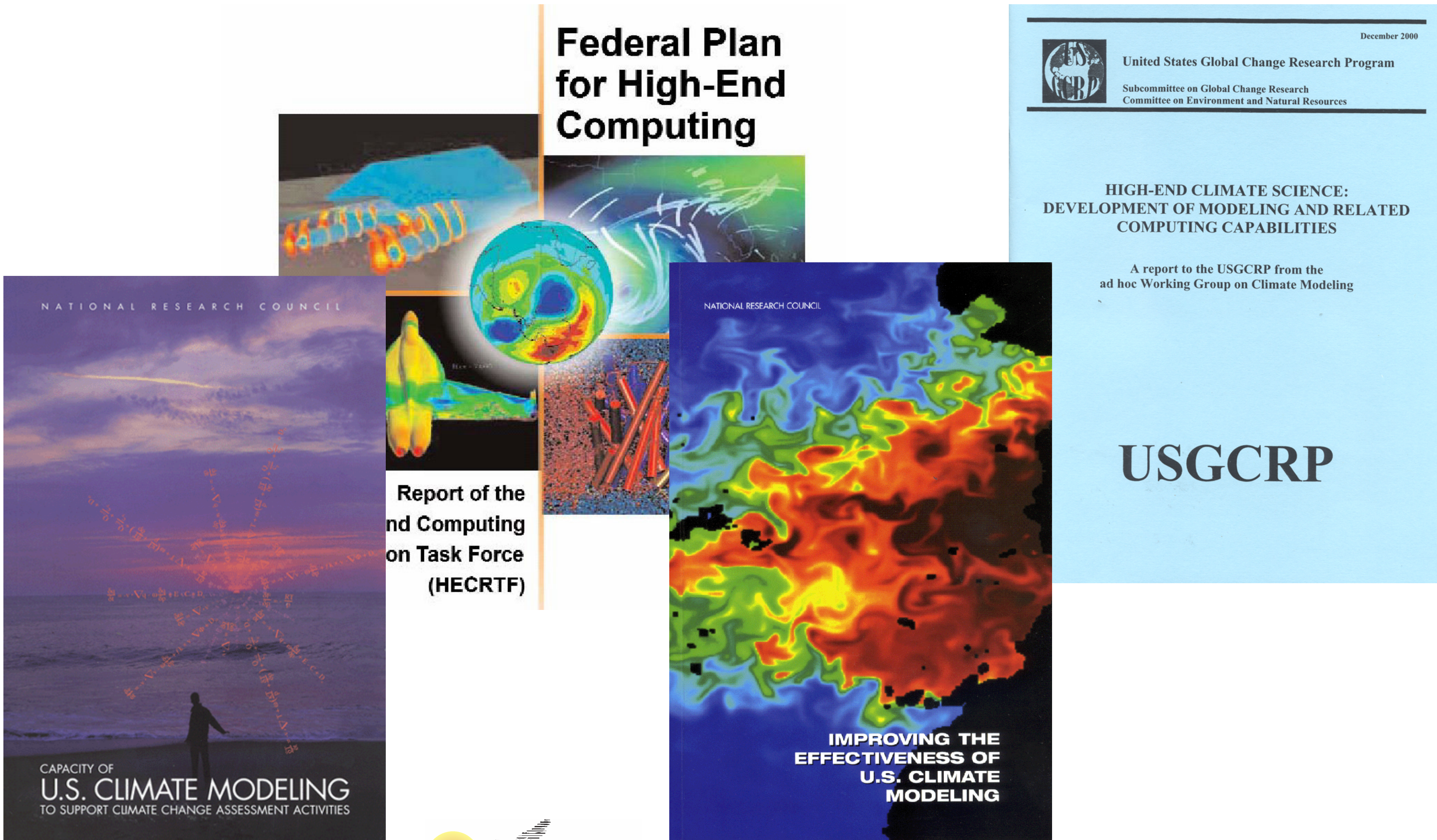
We Need Scalability, Balance, and a Stable Programming Model!!!



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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

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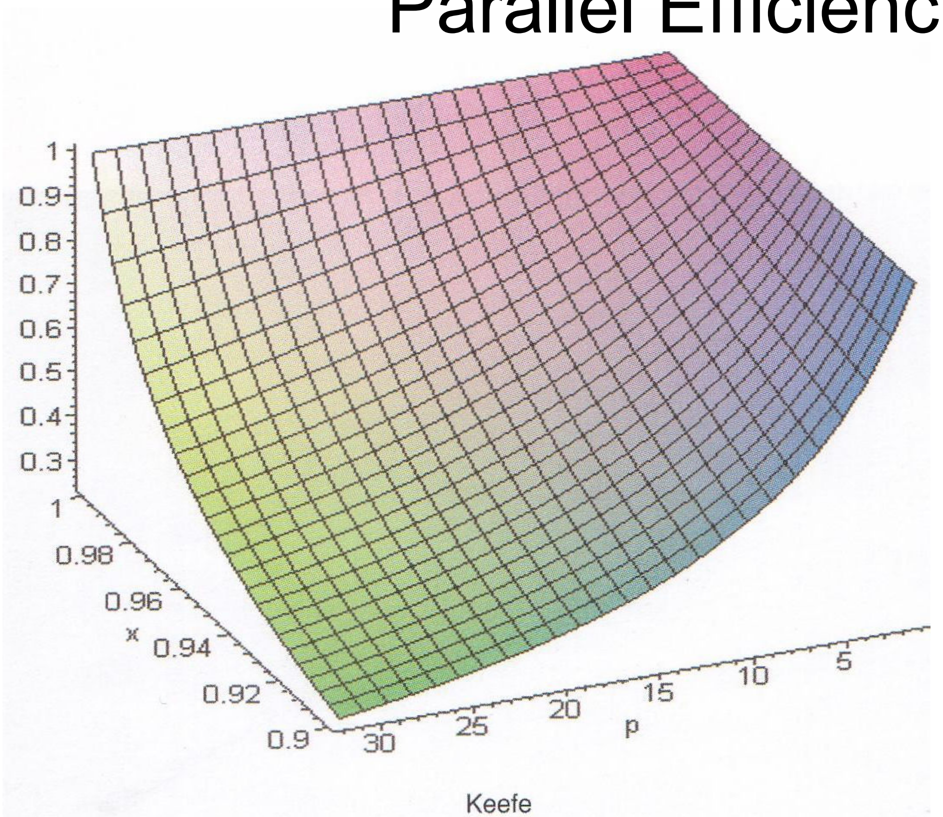
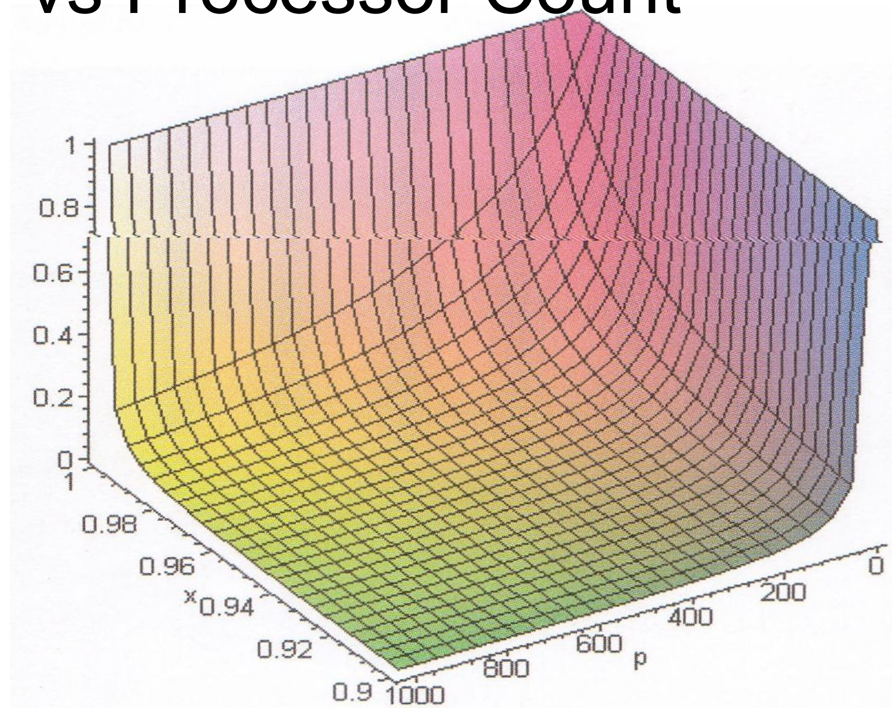
Scalability and Amdahl's Law

Parallel Efficiency vs Processor Count



1 - 32 Processor System



40-1024 Processor System

Ref: NRC, 2001

HECRTF Report Appendix D:
DISCUSSION ON SYSTEM SPECIFICATIONS AND APPLICATION REQUIREMENTS

- Scalable MPP and cluster systems, while providing massive amounts of memory, are inherently more difficult to program.
- Numerous attempts are currently under way to retool codes in application areas such as … global climate modeling, … to run more efficiently on MPP architectures, simply because they are the most plentiful systems currently available…
- ….while they have resulted in more scalable codes in the short run, have diverted attention away from the development of systems that provide high-bandwidth access to extremely large global memories.

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)

The End