# An Introduction to Climate Modeling

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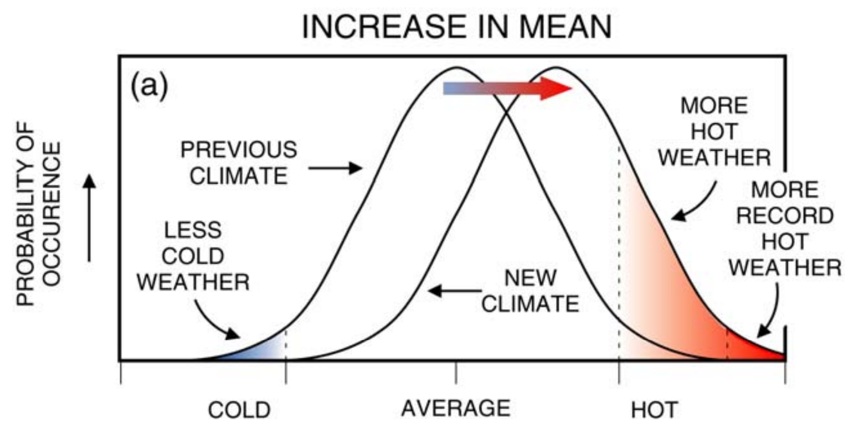
# Outline

- What is Climate & why do we care
- Hierarchy of atmospheric modeling strategies
  - 1D Radiative Convective models
  - 3D General Circulation models (GCMs)
- Conceptual Framework for General Circulation Models
- Scale interaction problem
  - concept of resolvable and unresolvable scales of motion
- Parameterization of physical processes
  - approaches rooted in budgets of conserved variables
- Model Validation and Model Solutions

# Question 1: How can we predict Climate (50 yrs) if we can't predict Weather (10 days)?

# Question 2: What is Climate?

- Average Weather
- Record high and low temperatures
- The temperature range
- Distribution of possible weather
- Extreme events




## *(1) What is Climate?*

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

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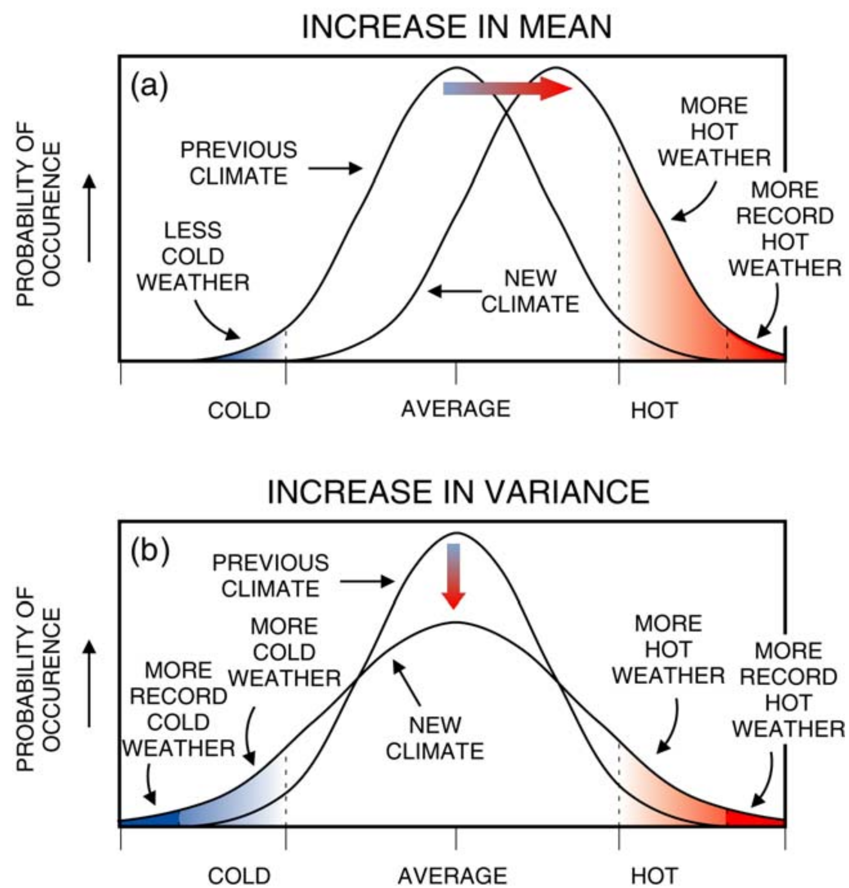


***Climate change and its manifestation in terms of weather (climate extremes)***

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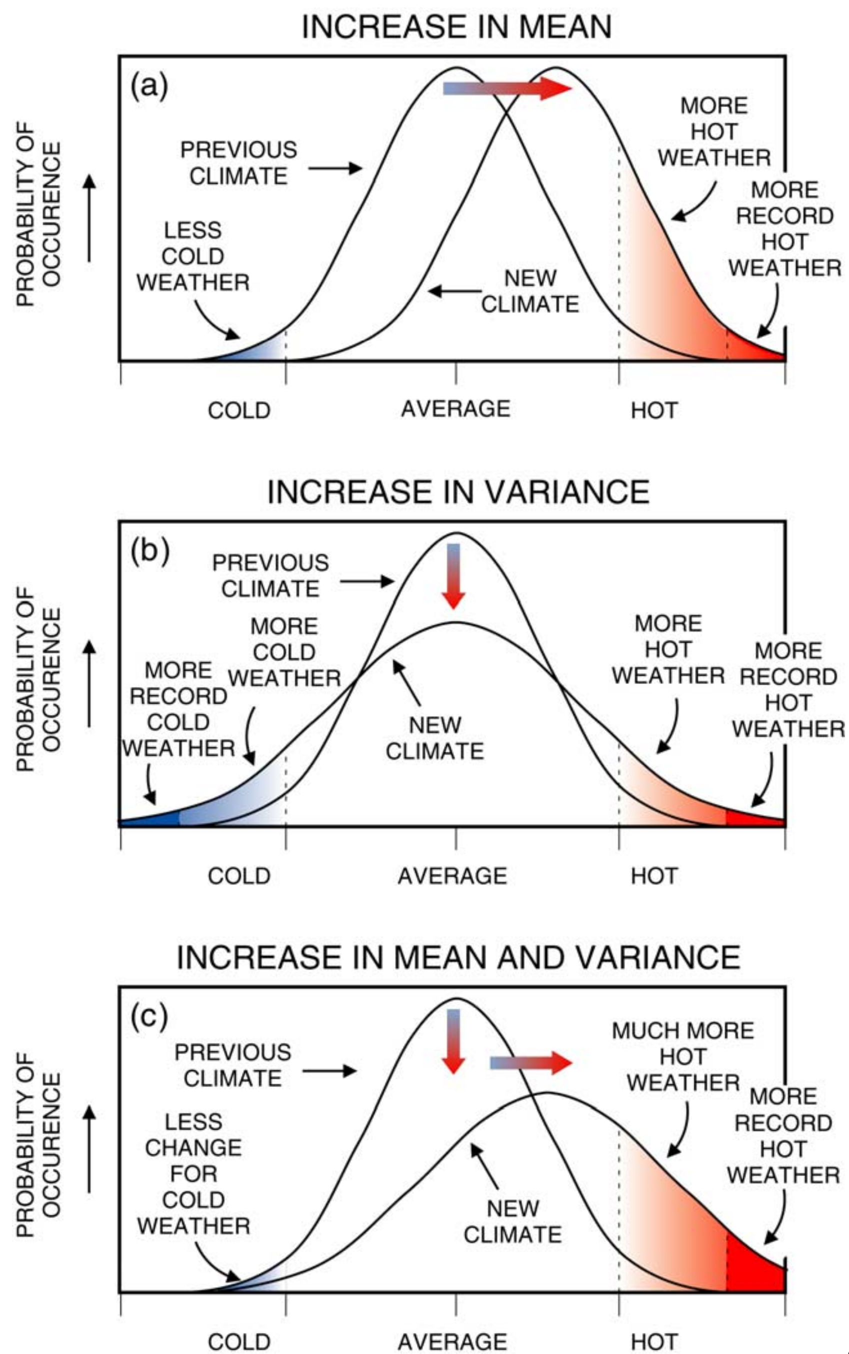
***Climate change and its manifestation in terms of weather (climate extremes)***

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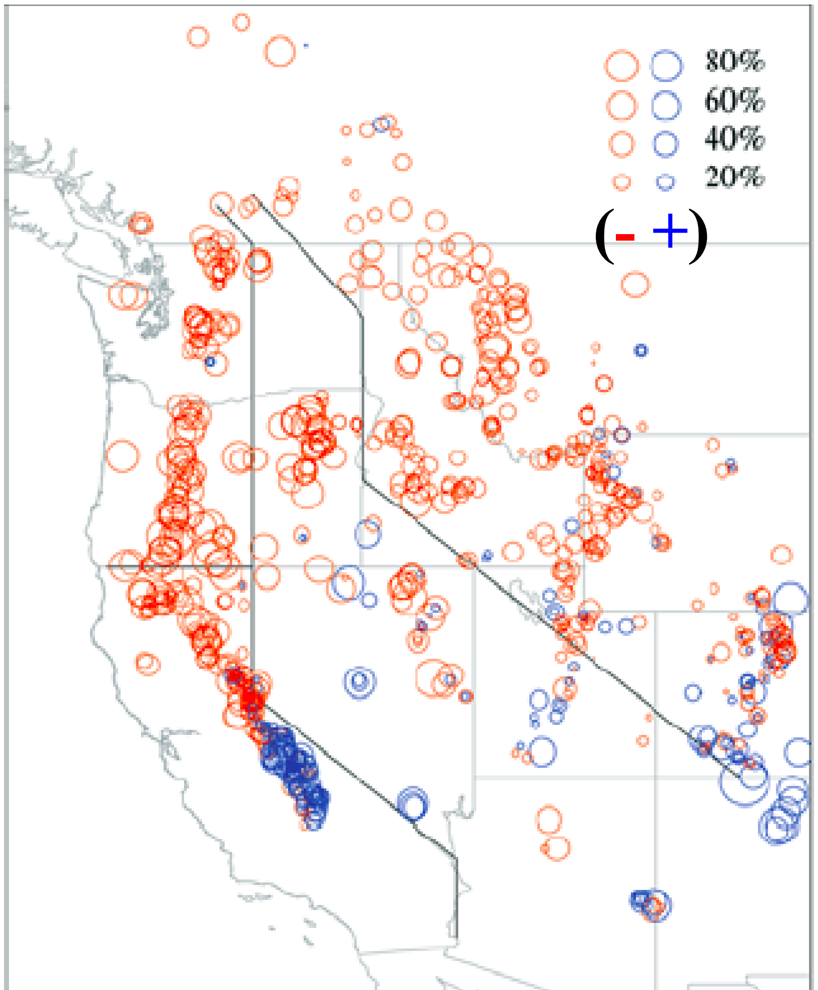
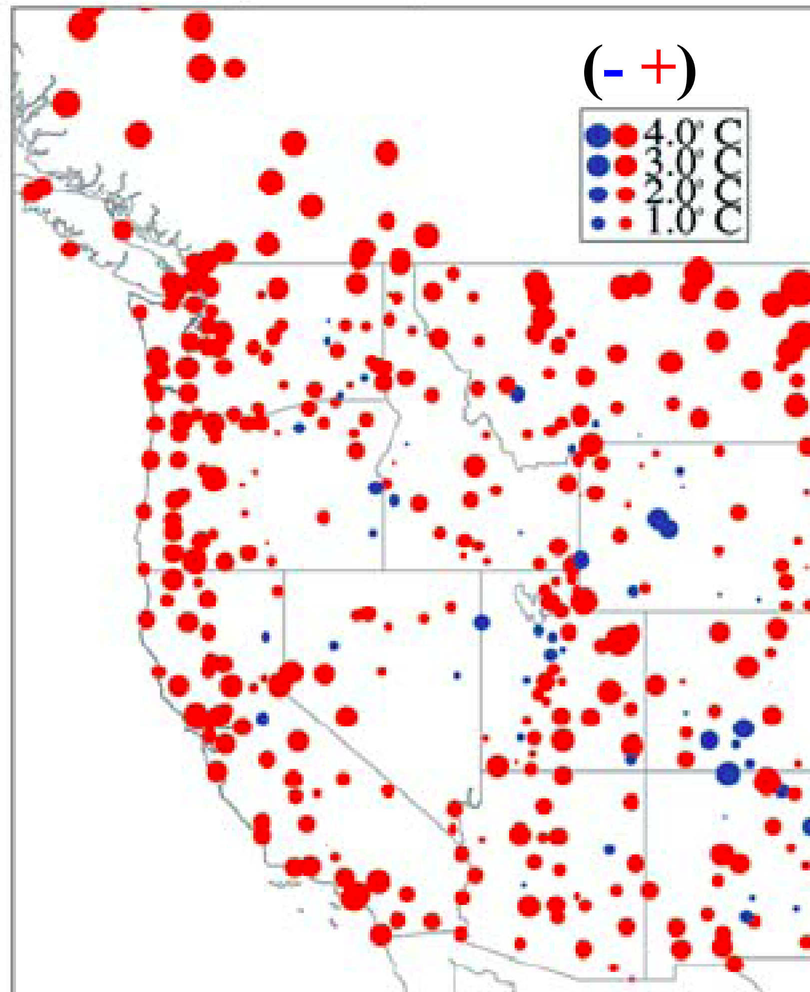
# Impacts of Climate Change

## Observed Change 1950-1997

### Snowpack




### Temperature




Mote et al 2005

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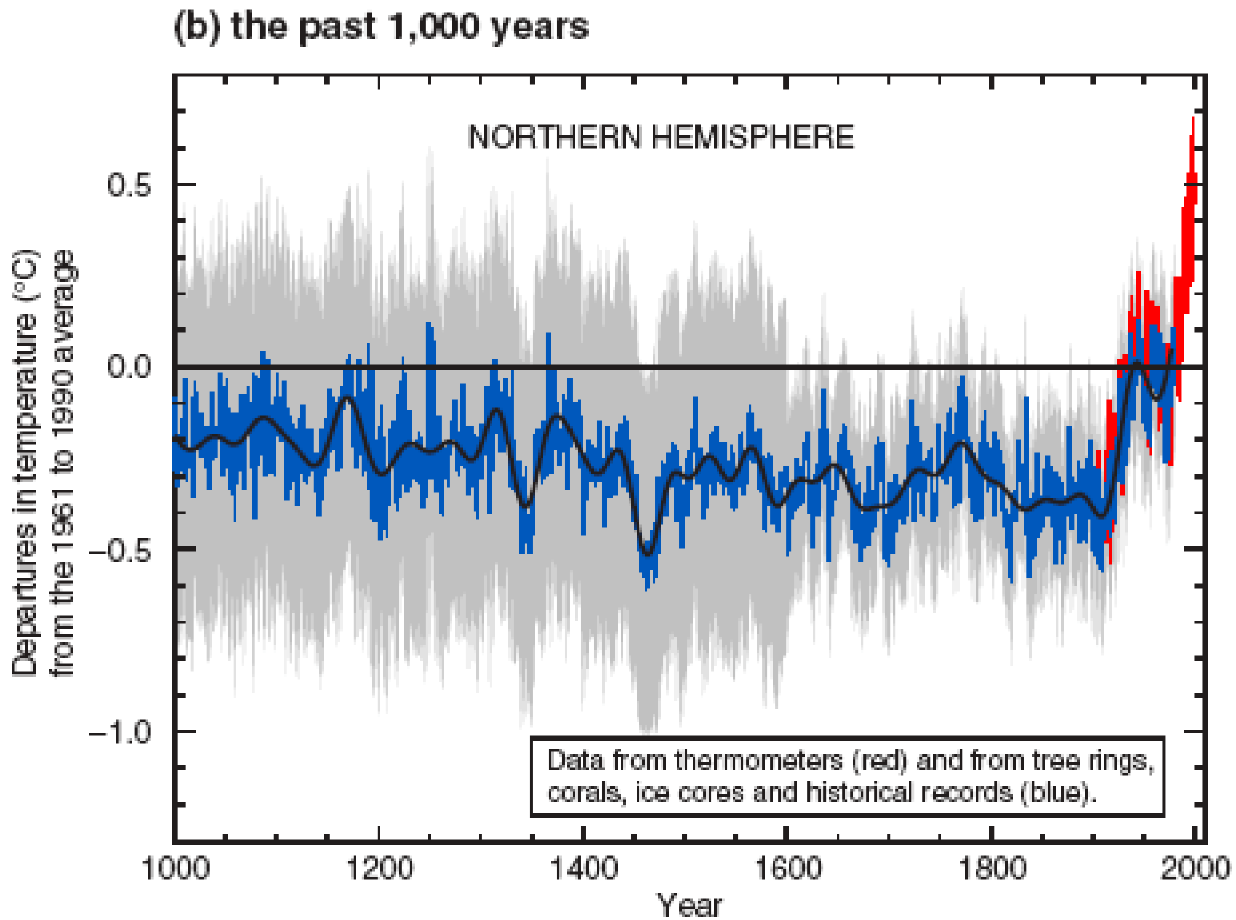
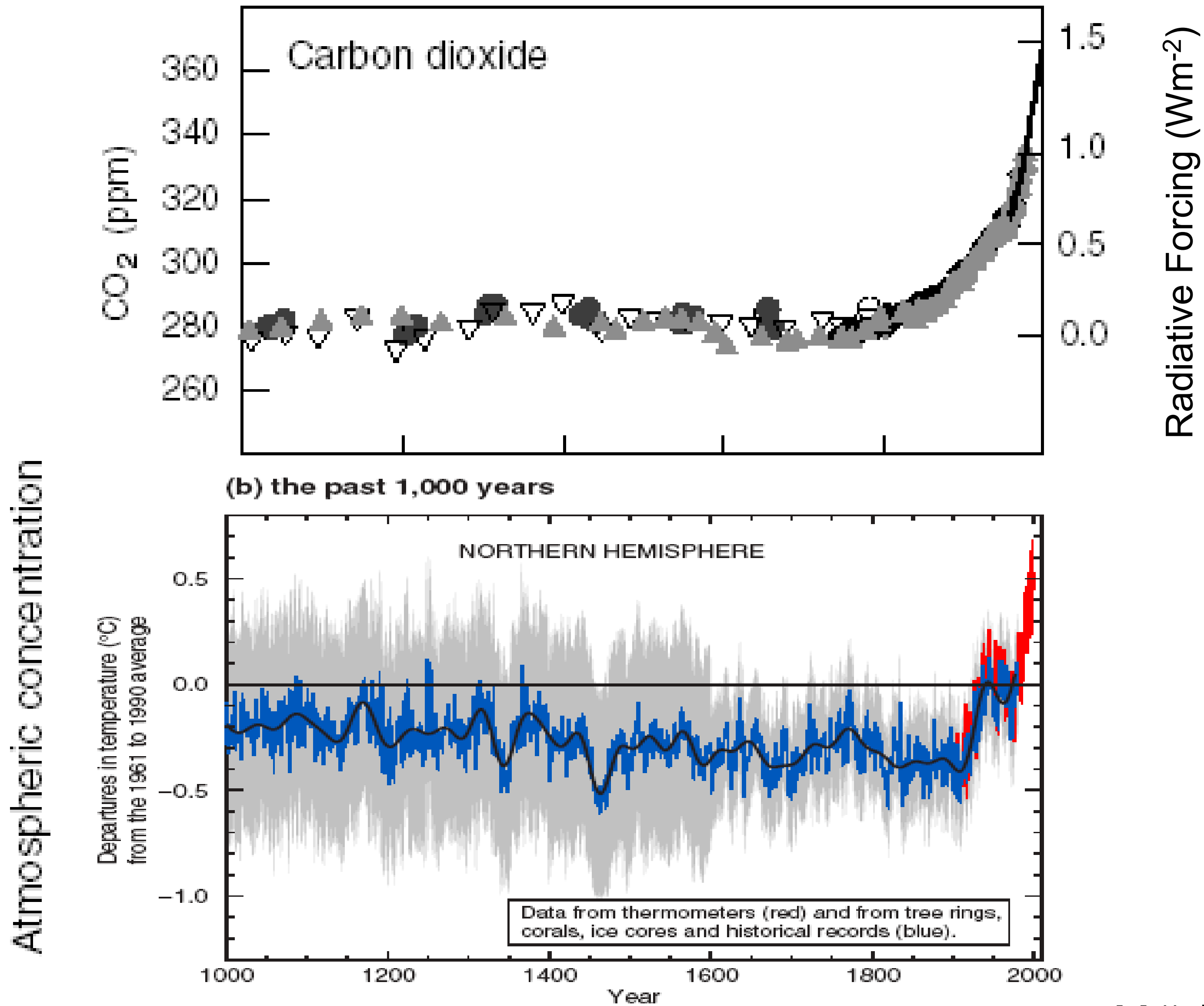
# Observed Temperature Records




IPCC, 3rd Assessment, Summary For Policymakers

# ‘Anthropogenic’ Changes

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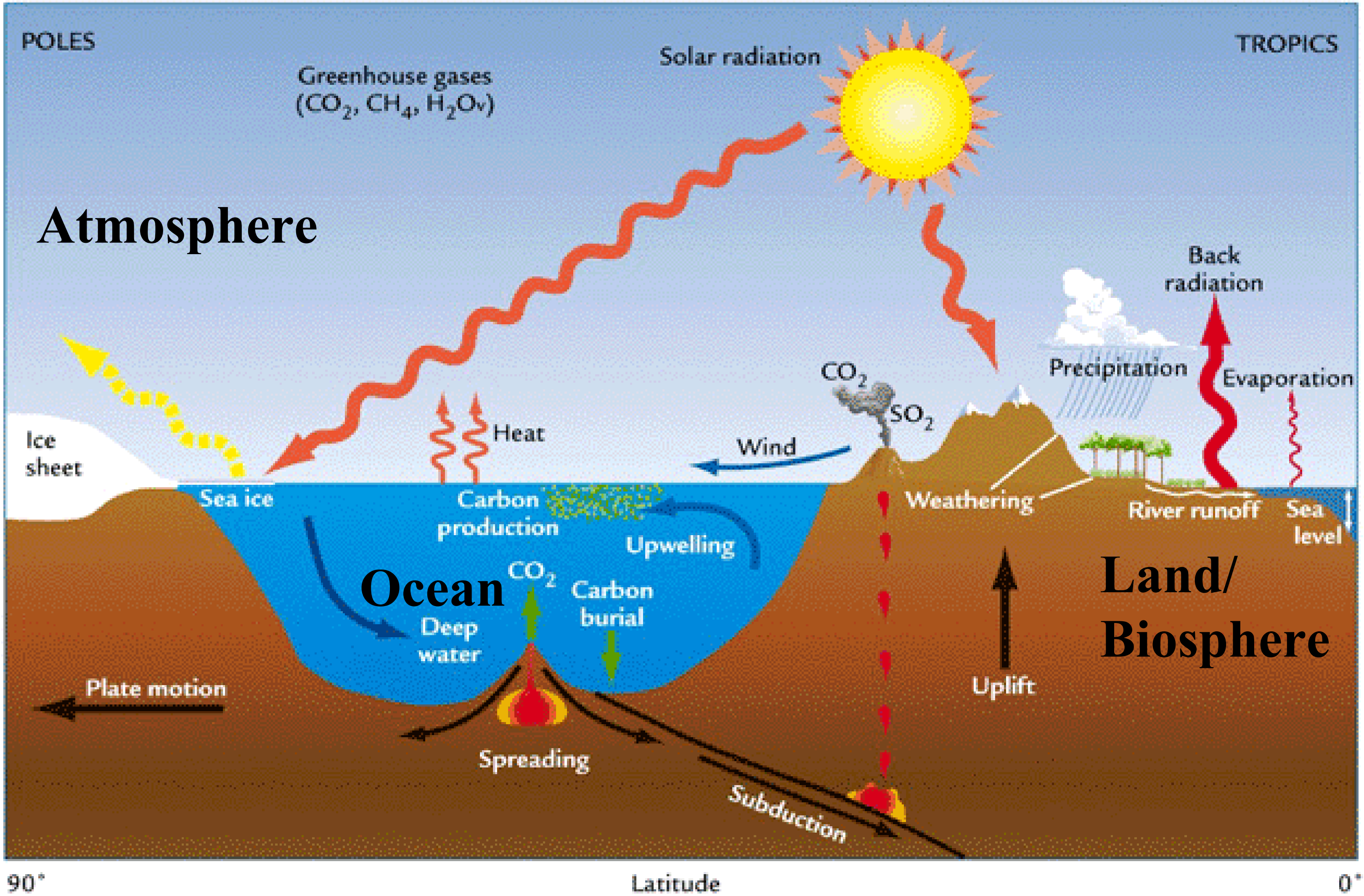
# The Earth's climate system




Pole

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Equator

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# Principles of Atmospheric Modeling

- Scientific basis for atmospheric simulation
  - rooted in laws of classical mechanics/thermodynamics
    - developed during 18th and 19th centuries (see Thompson, 1978)
  - early mathematical model described by Arrhenius (1896)
    - surface energy balance model

- Two modeling approaches developed over last century
  - based on energy balance requirements
  - dynamical models (e.g., explicit transports)

# Conceptual Framework for Modeling

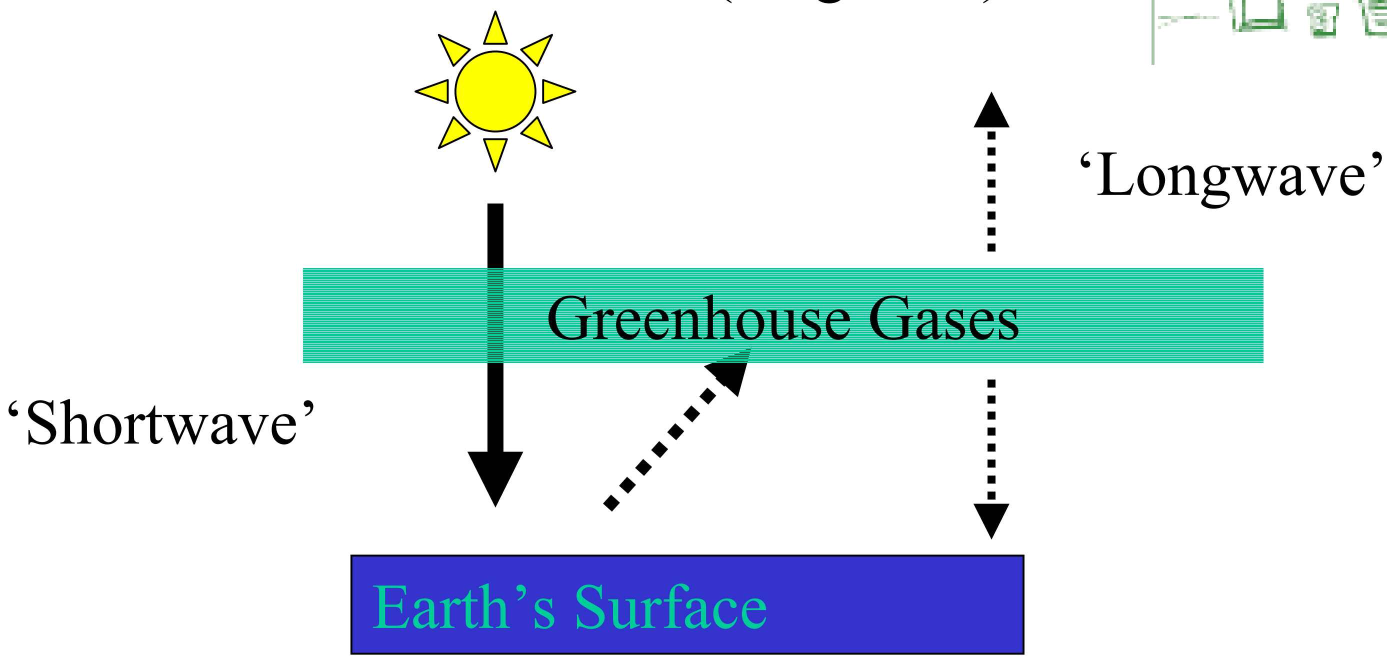
- Can't resolve all scales, so have to represent them

- Energy Balance / Reduced Models
  - Mean State of the System
  - Energy Budget, conservation, Radiative transfer
- Dynamical Models
  - Finite element representation of system
  - Fluid Dynamics on a rotating sphere
  - Basic equations of motion
  - Physical Parameterizations for moving energy

# What is the greenhouse Effect?

Greenhouses Trap Heat

Analogous to Atmosphere:
- Glass is transparent in Visible(shortwave)
- Glass absorbs in Infrared (longwave)




Major Greenhouse Gases: Water Vapor, Carbon Dioxide, Methane

# Atmospheric modeling hierarchy

*Understanding has been aided by a hierarchy of approaches*

Consider the flux form of thermodynamic energy equation

$$c_p \frac{\partial T}{\partial t} = -c_p \nabla \cdot (\mathbf{V}T) - c_p \frac{\partial(\omega T)}{\partial p} + c_p \frac{\kappa \omega T}{p} + Q_{\mathrm{rad}} + Q_{\mathrm{conv}} \qquad (1)$$

where $T$ - temperature; $\mathbf{V}$ - horizontal wind vector; $p$ - pressure; $\omega$ - vertical pressure velocity; $Q_{\mathrm{rad}}$ and $Q_{\mathrm{conv}}$ - net radiative and convective heating

- Simple Zero-Dimensional (Energy Balance) Climate Model
  - Averaging (1) over horizontal and vertical space dimensions yields

$$c_p \frac{\partial < \hat{T} >}{\partial t} = < S > - < F >$$

where $S$ is net absorbed solar radiation and $F$ is longwave radiation emmitted to space

For a long-term stable climate, $< S > - < F > = 0$

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# Atmospheric modeling hierarchy

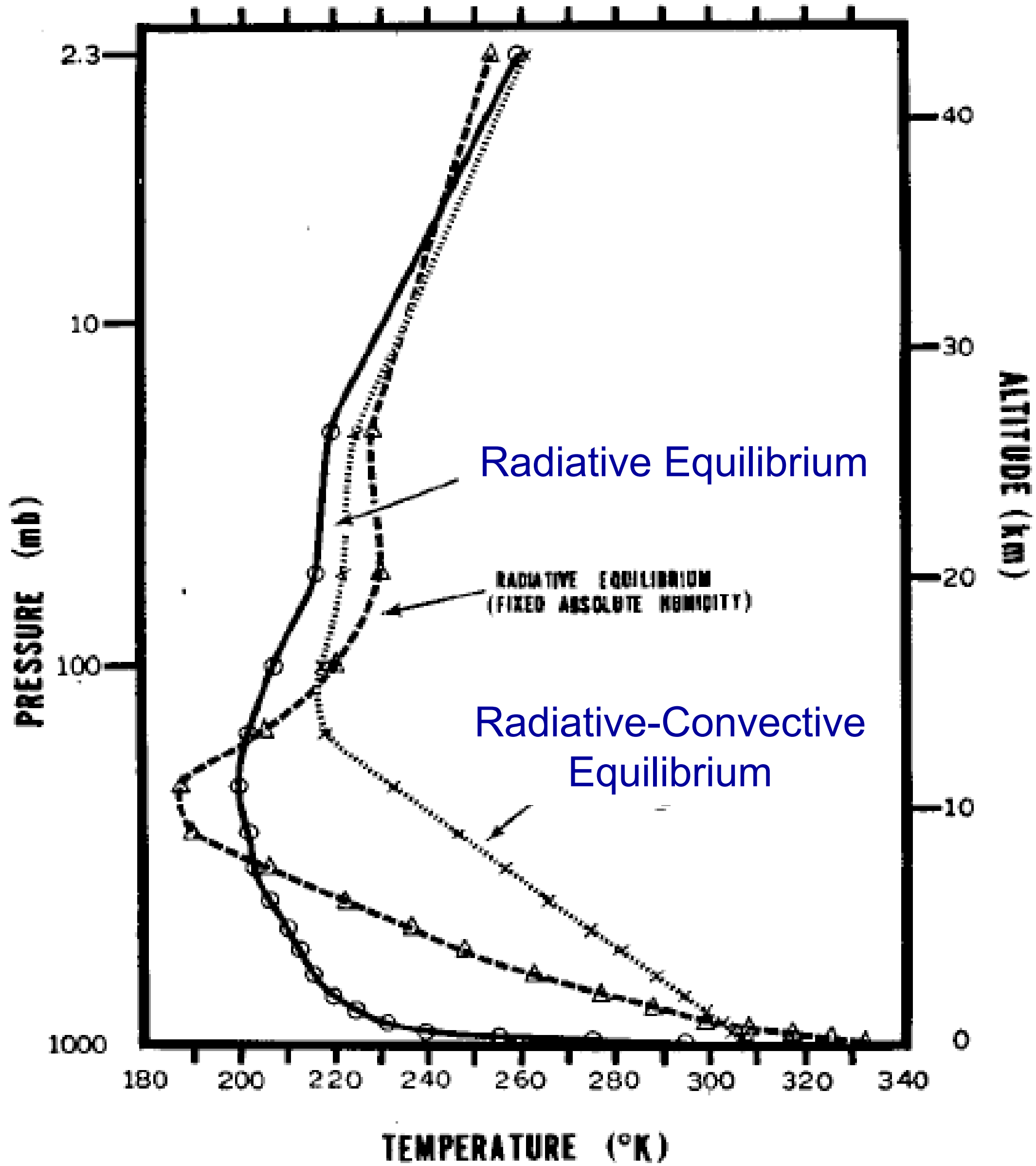
- Simple One-Dimensional (Radiative-Convective) Climate Model
  - Averaging (1) over horizontal space dimensions yields

$$c_p \frac{\partial < T >}{\partial t} = < Q_{\text{rad}} > + < Q_{\text{conv}} >$$

where a globally averaged vertical profile of $T$ can be determined from expressions for $< Q_{\text{rad}} >$ and $< Q_{\text{conv}} >$

- Higher-order models determined by form of averaging operators

# 1D Radiative Convective Model




Manabe
& Wetherald 1967

# 1D models: Doubling CO2

TABLE 5. Change of equilibrium temperature of the earth's surface corresponding to various changes of $CO_2$ content of the atmosphere.

| Change of $CO_2$ content (ppm) | Fixed absolute humidity | | Fixed relative humidity | |
|---|---|---|---|---|
| | Average cloudiness | Clear | Average cloudiness | Clear |
| 300 → 150 | −1.25 | −1.30 | −2.28 | −2.80 |
| 300 → 600 | +1.33 | +1.36 | +2.36 | 2.92 |

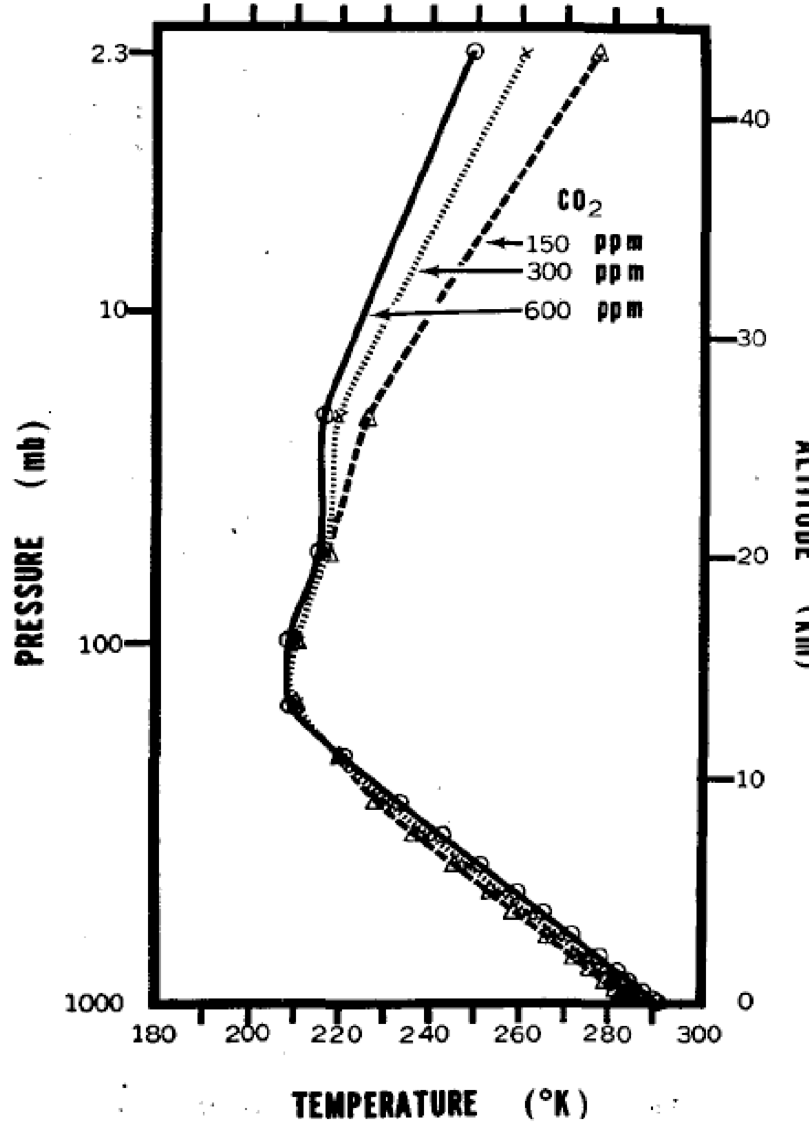
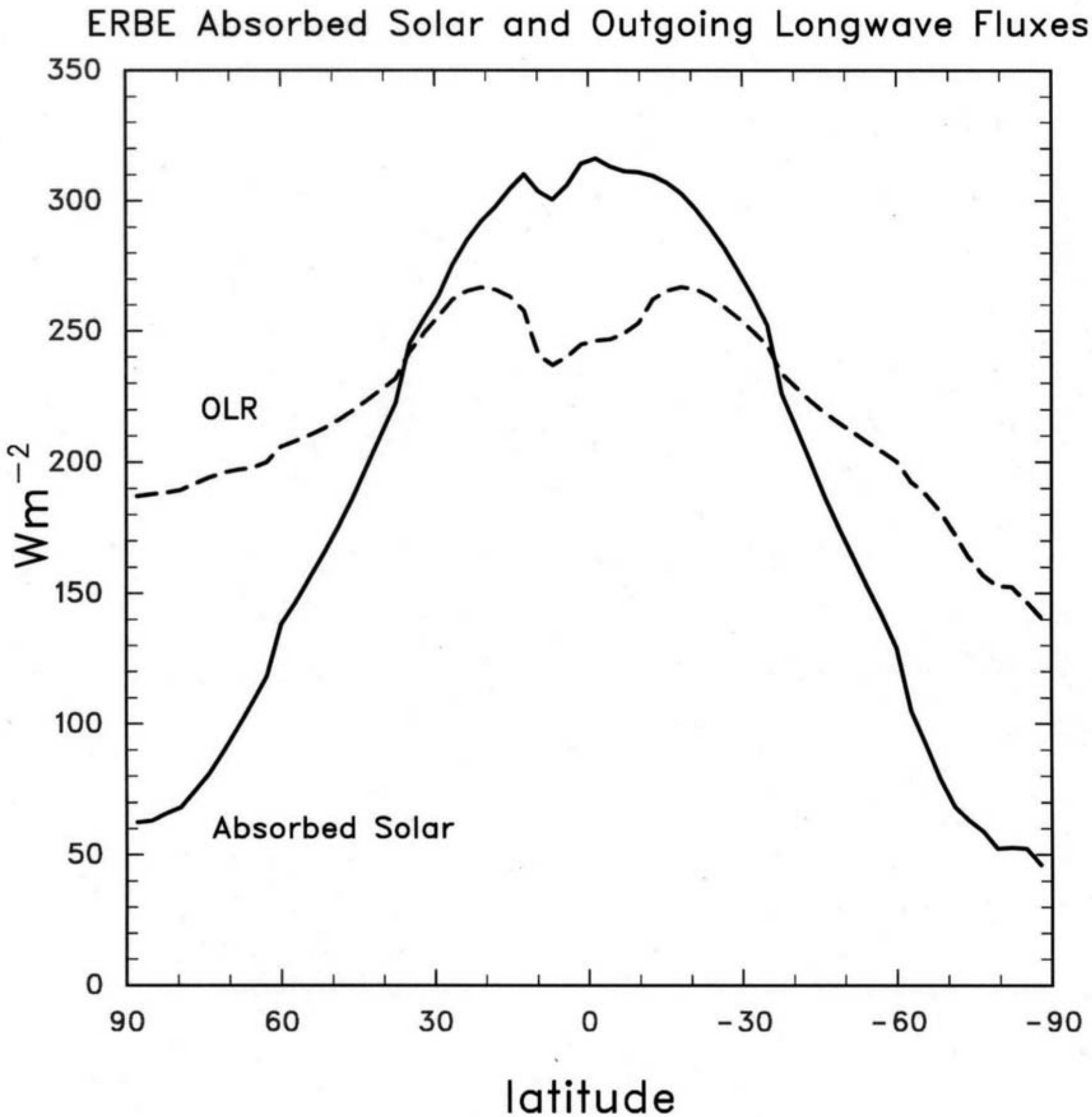



FIG. 16. Vertical distributions of temperature in radiative convective equilibrium for various values of $CO_2$ content.

Manabe & Wetherald 1967

# Top of Atmosphere Radiation Component Fluxes

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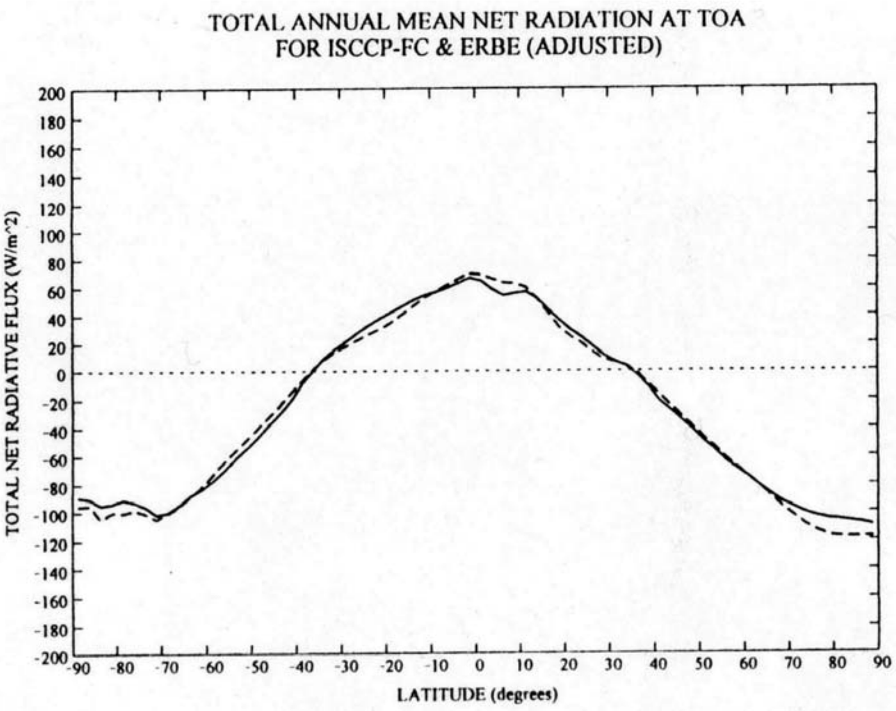
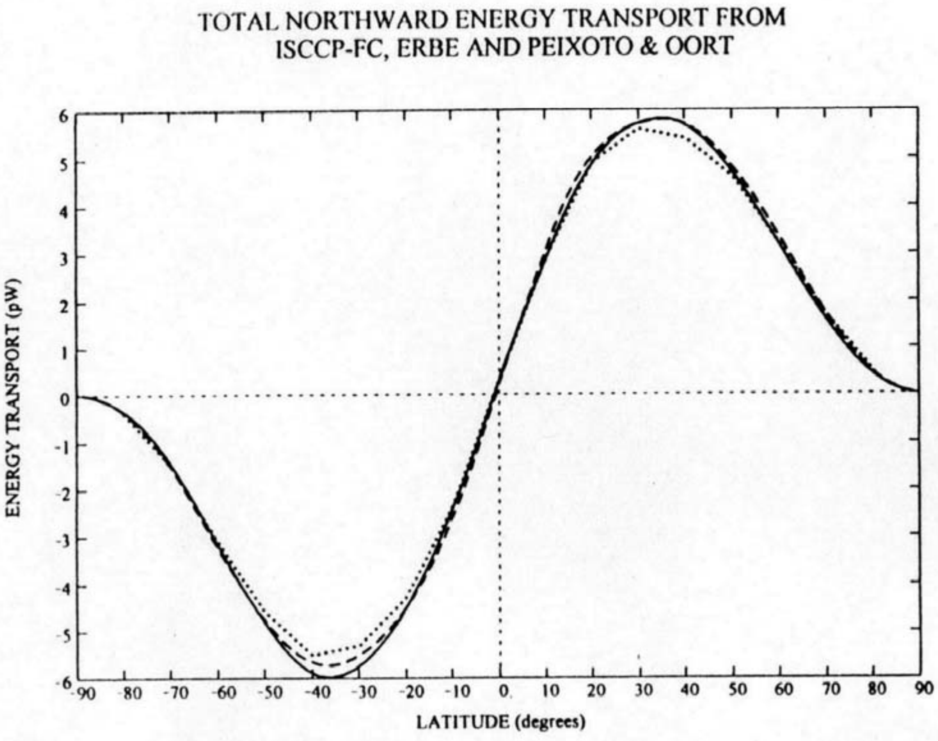
# Top of Atmosphere Net Radiation Budget and Implied Meridional Energy Transport




*Zhang and Rossow (1997)*

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# Atmospheric General Circulation Models and Climate Simulation

- Reduced models of the climate system
  - apply "averaging operator" to governing equations

- Atmospheric General Circulation Models (AGCMs)
  - simulate detailed "weather" fluctuations in the fluid system
  - day-to-day solution details are non-deterministic (Lorenz, 1962)
  - apply "averaging operator" to detailed solution sequence
  - utility lies in prediction of statistical properties of the fluid system
    - *chronological sequence of intermediate states unimportant*

# Physical processes regulating climate

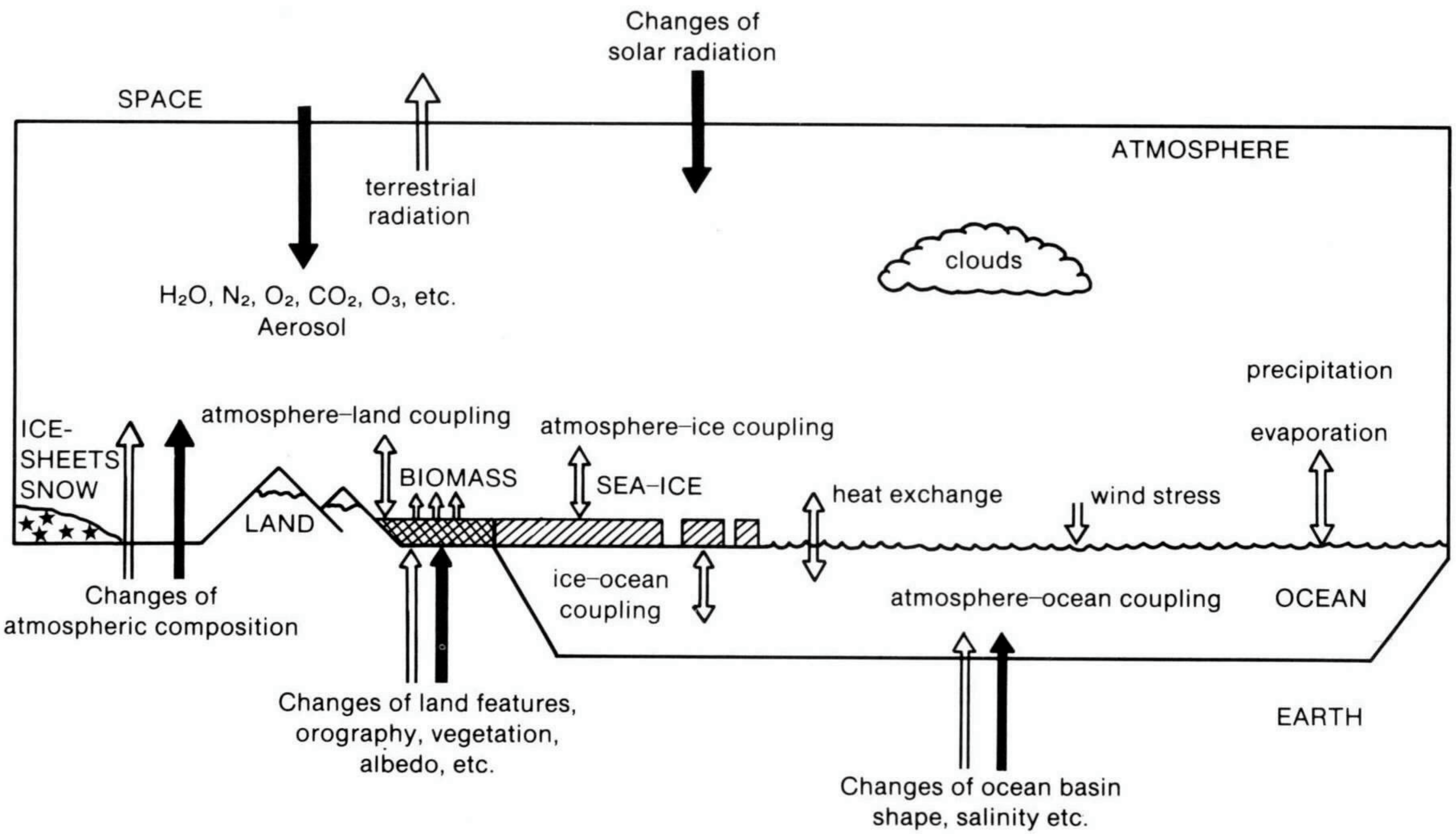


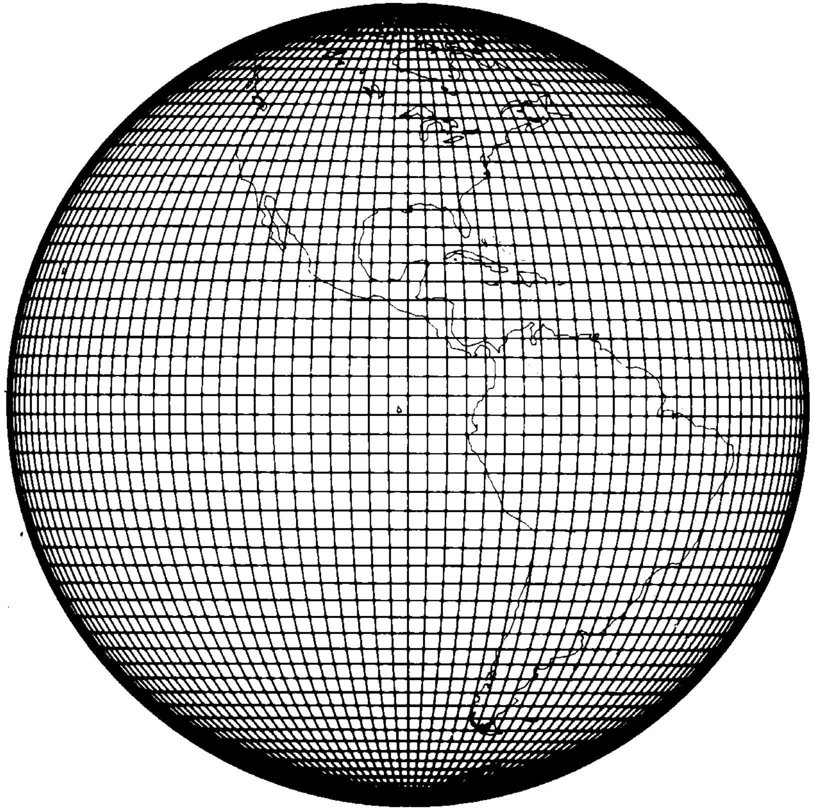

**Figure 3.1:** Schematic illustration of the components of the coupled atmosphere-ocean-ice-land climatic system. The full arrows are examples of external processes, and the open arrows are examples of internal processes in climatic change (from Houghton, 1984).

# Modeling the Atmospheric General Circulation

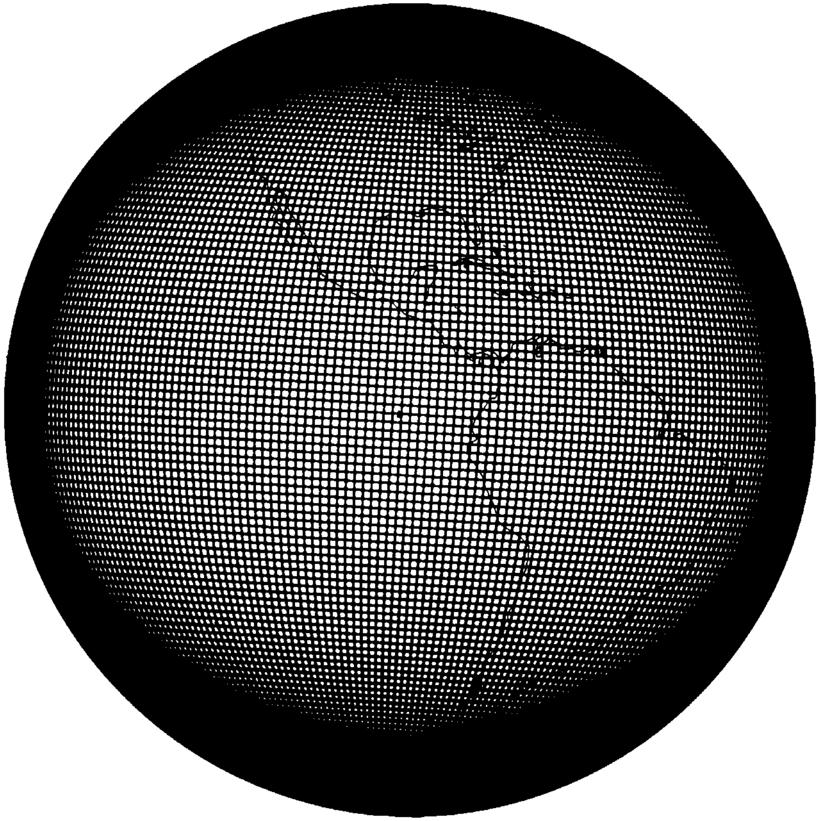
## Understanding of climate & global scale dynamics

- atmospheric predictability/basic fluid dynamics
- physics/dynamics of phase change
- radiative transfer (aerosols, chemical constituents, etc.)
- atmospheric chemistry (trace gas sources/sinks, acid rain, etc.)
- interactions between the atmosphere and ocean (e.g., El Nino, etc.)
- solar physics (solar-terrestrial interactions, solar dynamics, etc.)
- impacts of anthropogenic and other biological activity

# Examples of Global Model Resolution



Typical Climate Application



Next Generation Climate Applications

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# Meteorological Primitive Equations

- Applicable to wide scale of motions; > 1hour, >100km

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F}, \qquad \textit{(horizontal momentum)}$$

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p, \qquad \textit{(thermodynamic energy)}$$

$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0, \qquad \textit{(mass continuity)}$$

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0, \qquad \textit{(hydrostatic equilibrium)}$$

$$d\overline{q}/dt = S_q. \qquad \textit{(water vapor mass continuity)}$$

**Harmless looking terms F, $Q$, and $S_q \Longrightarrow$ "physics"**

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# Global Climate Model Physics

Terms *F, Q,* and $S_q$ represent physical processes

- Equations of motion, *F*
  - turbulent transport, generation, and dissipation of momentum
- Thermodynamic energy equation, *Q*
  - convective-scale transport of heat
  - convective-scale sources/sinks of heat (phase change)
  - radiative sources/sinks of heat
- Water vapor mass continuity equation
  - convective-scale transport of water substance
  - convective-scale water sources/sinks (phase change)

# Model Physical Parameterizations

Physical processes breakdown:

- Moist Processes
  - Moist convection, shallow convection, large scale condensation
- Radiation and Clouds
  - Cloud parameterization, radiation
- Surface Fluxes
  - Fluxes from land, ocean and sea ice (from data or models)
- Turbulent mixing
  - Planetary boundary layer parameterization, vertical diffusion, gravity wave drag

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# Basic Logic in a GCM (Time-step Loop)

For a grid of atmospheric columns:

- 'Dynamics': Iterate Basic Equations

  Horizontal momentum, Thermodynamic energy,

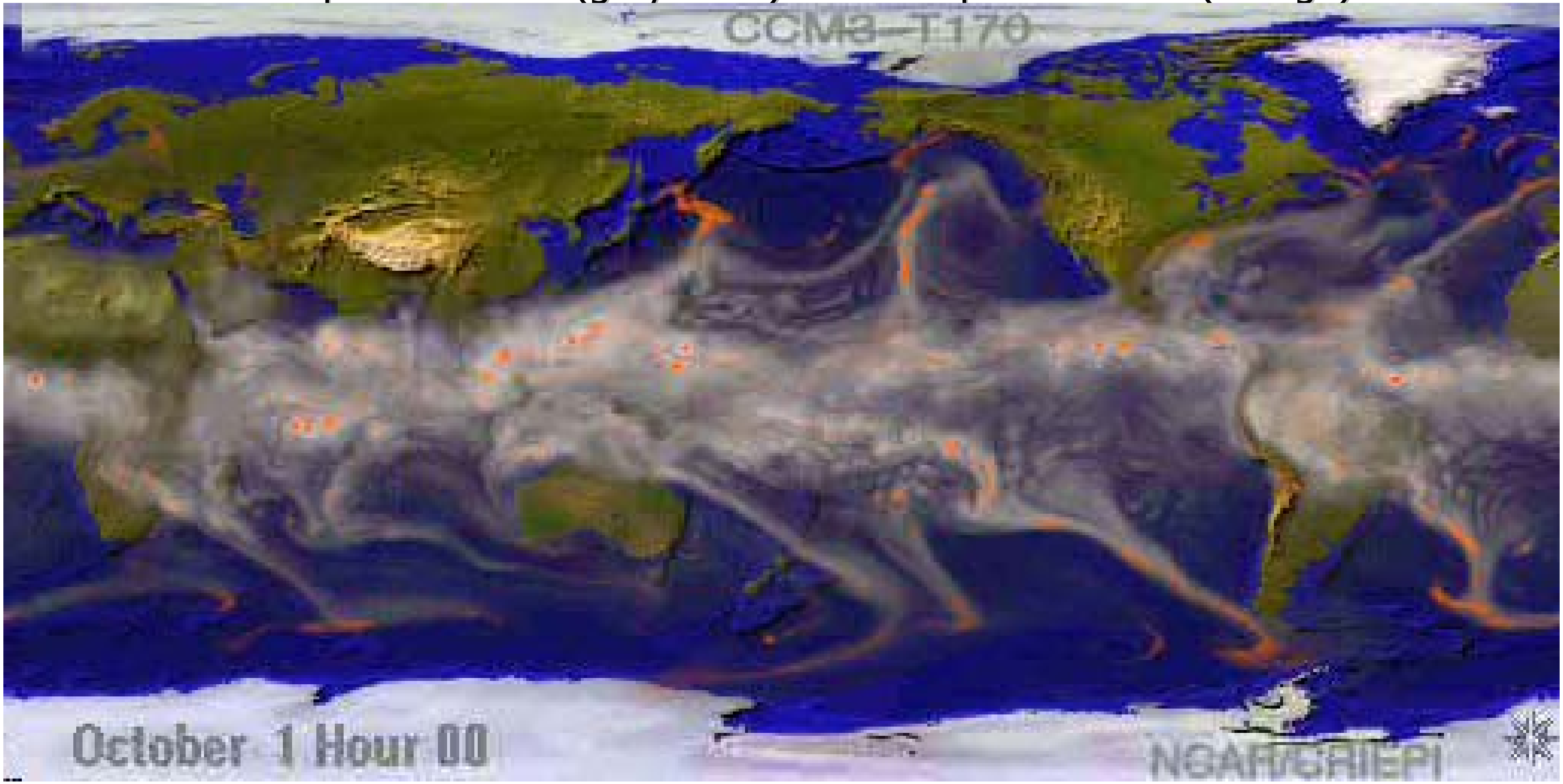
  Mass conservation, Hydrostatic equilibrium,

  Water vapor mass conservation
- Transport 'constituents' (water vapor, aerosol, etc)
- Calculate forcing terms ("Physics") for each column

  Clouds & Precipitation, Radiation, etc
- Update dynamics fields with physics forcings
- Next time step (repeat)

# *Example of State of the Art Global Model Simulation*

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




*Animation courtesy of NCAR SCD Visualization and Enabling Technologies Section*

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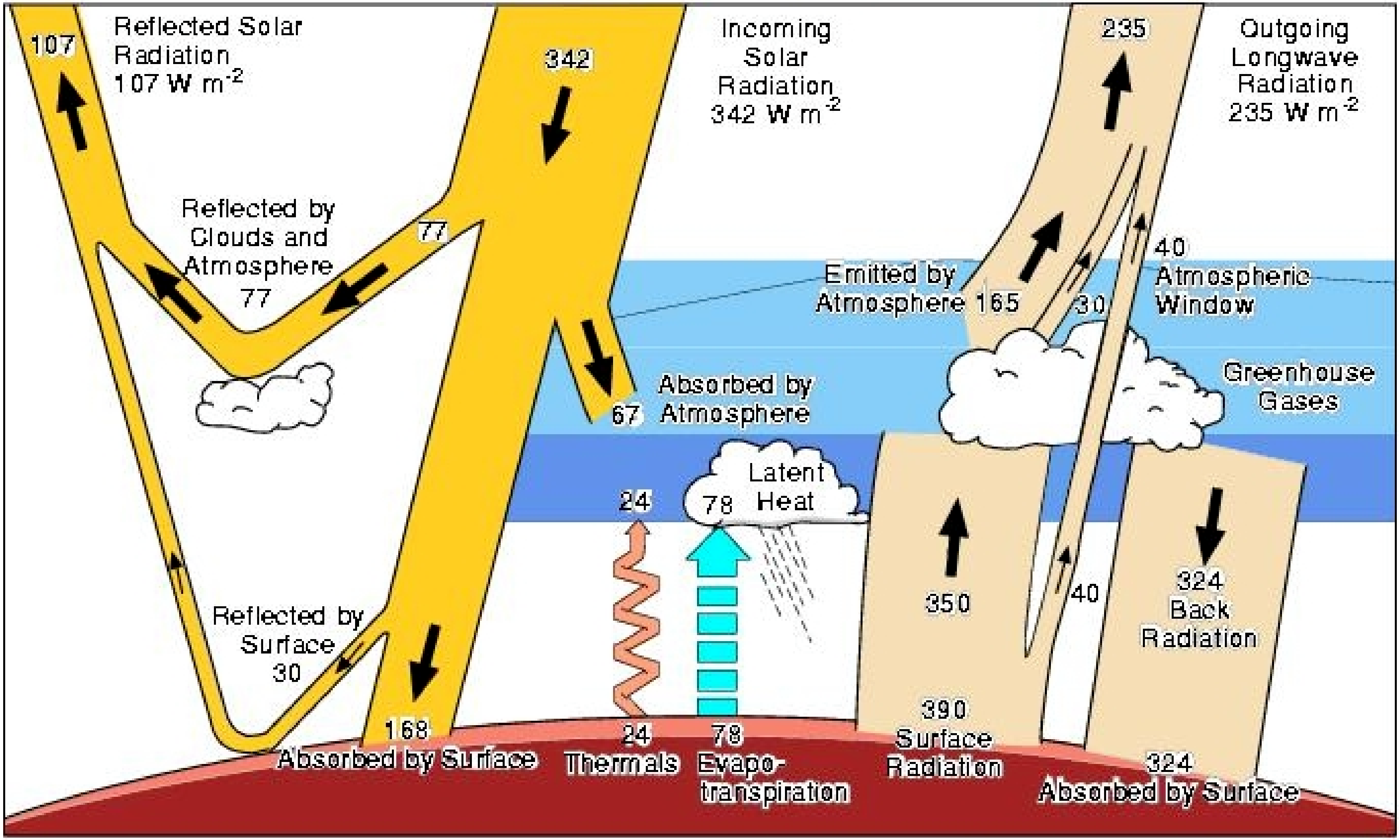
# Physical Parameterization

***To close the governing equations, it is necessary to incorporate the effects of physical processes that occur on scales below the numerical truncation limit***

- Physical parameterization
  - express unresolved physical processes in terms of resolved processes
  - generally empirical techniques
- Examples of parameterized physics
  - dry and moist convection
  - cloud amount/cloud optical properties
  - radiative transfer
  - planetary boundary layer transports
  - surface energy exchanges
  - horizontal and vertical dissipation processes
  - ...

# Radiation




*Kiehl and Trenberth 1997*

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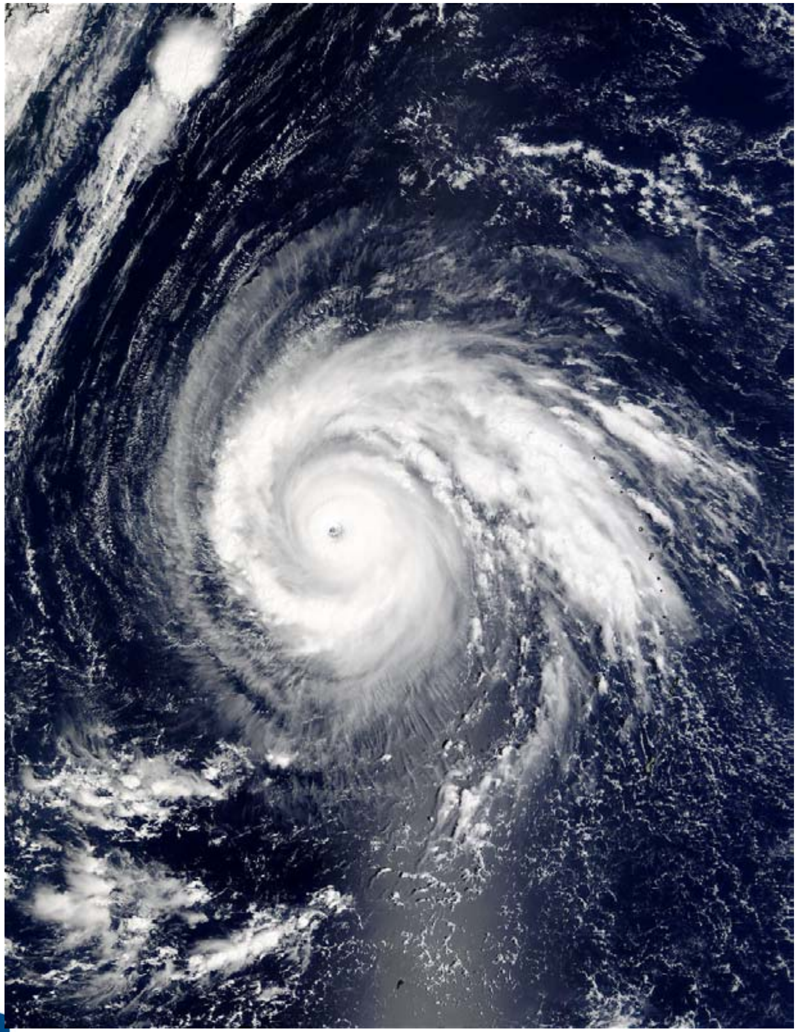
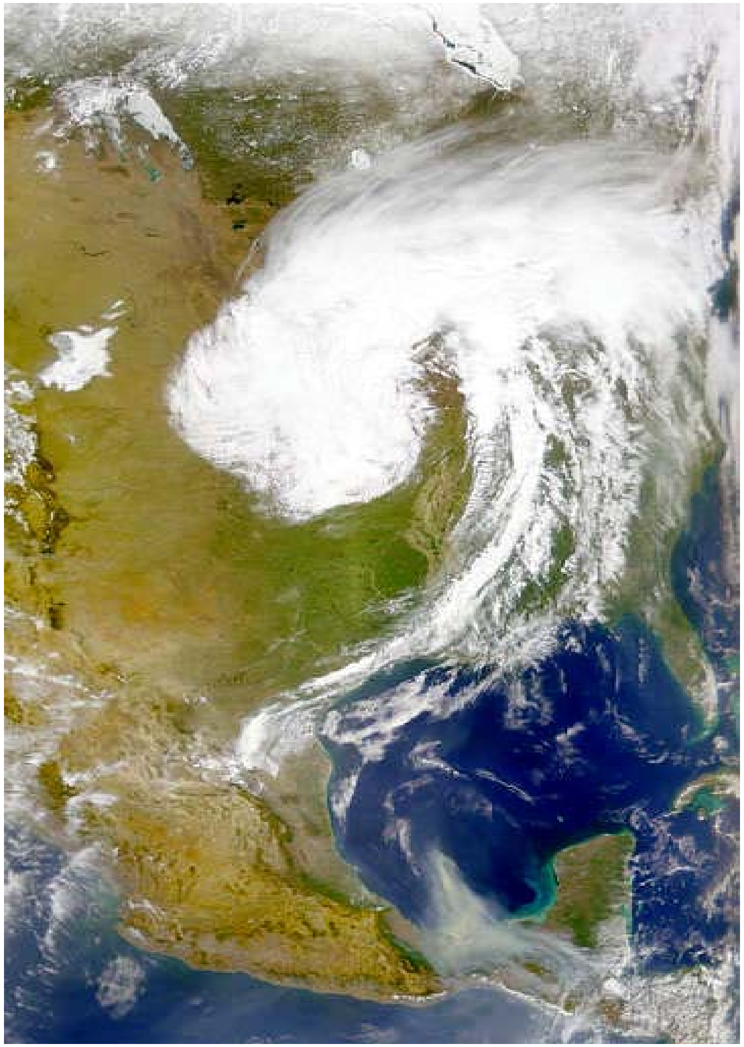
# Atmospheric Energy Transport

## Synoptic-scale mechanisms

• hurricanes



• extratropical storms



http://www.earth.nasa.gov

# Clouds are a fundamental component of larger-scale organized energy transport mechanisms

http://www.earth.nasa.gov

# Other Energy Budget Impacts From Clouds

http://www.earth.nasa.gov

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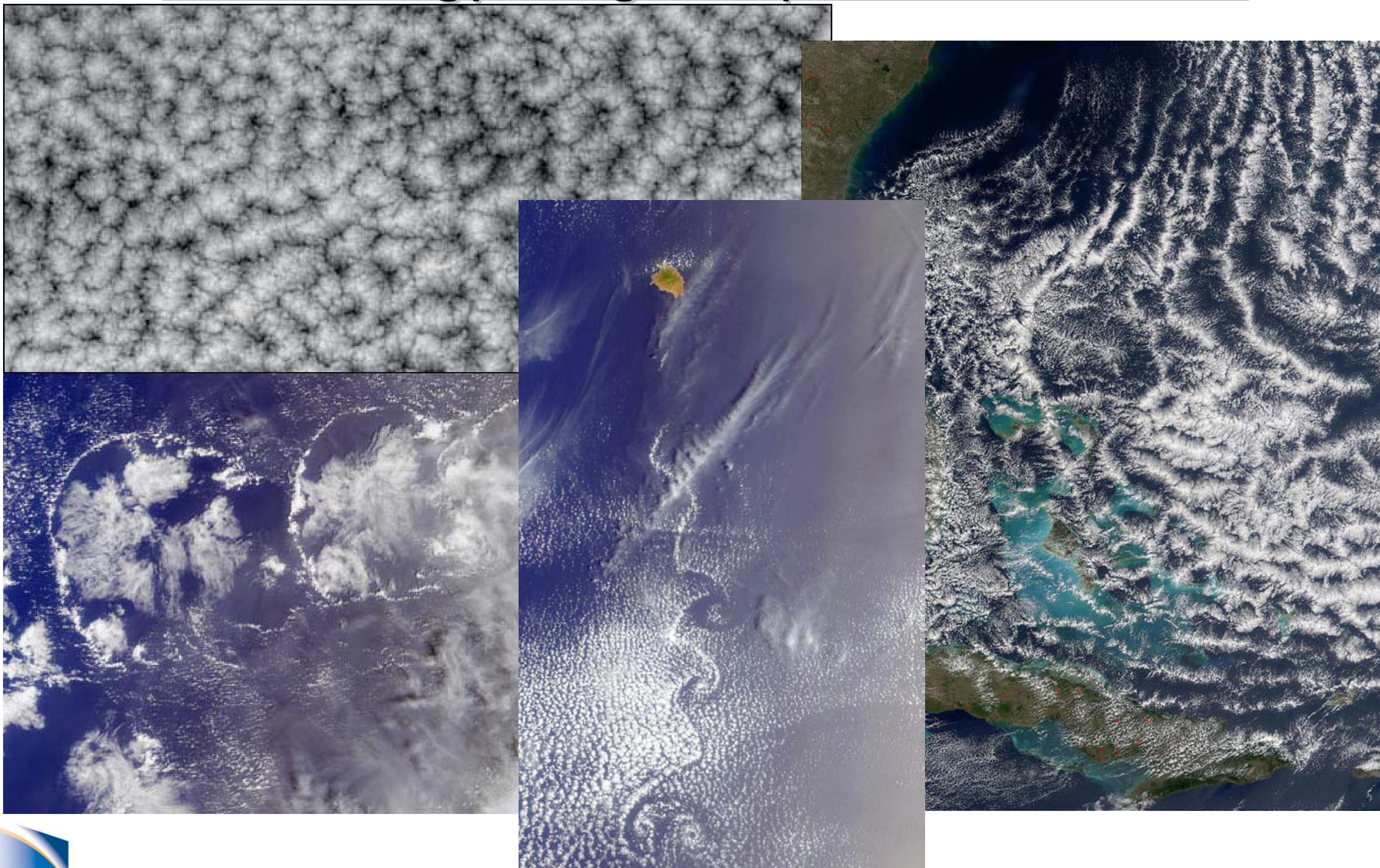
# Other Energy Budget Impacts From Clouds



http://www.earth.nasa.gov

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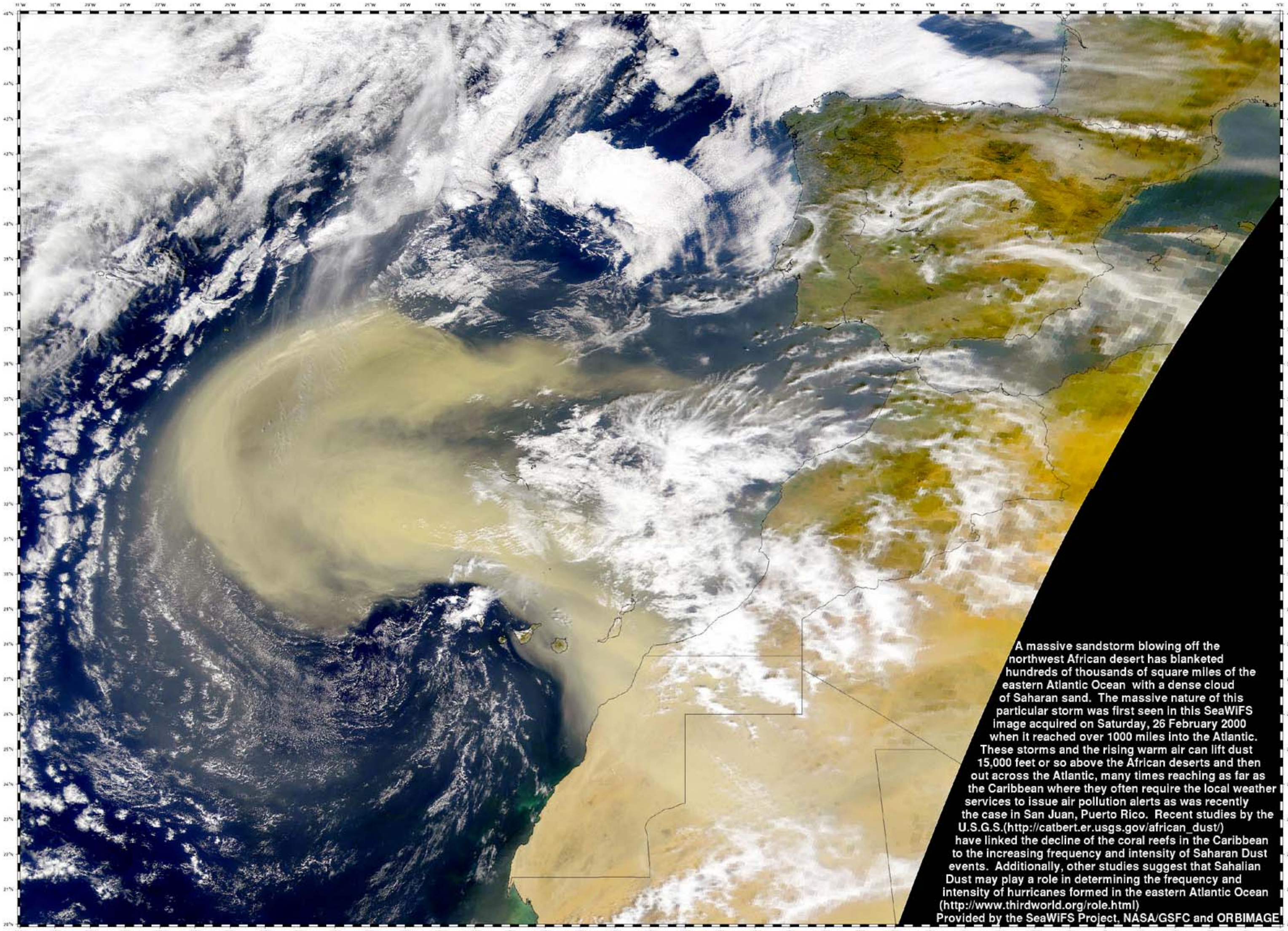
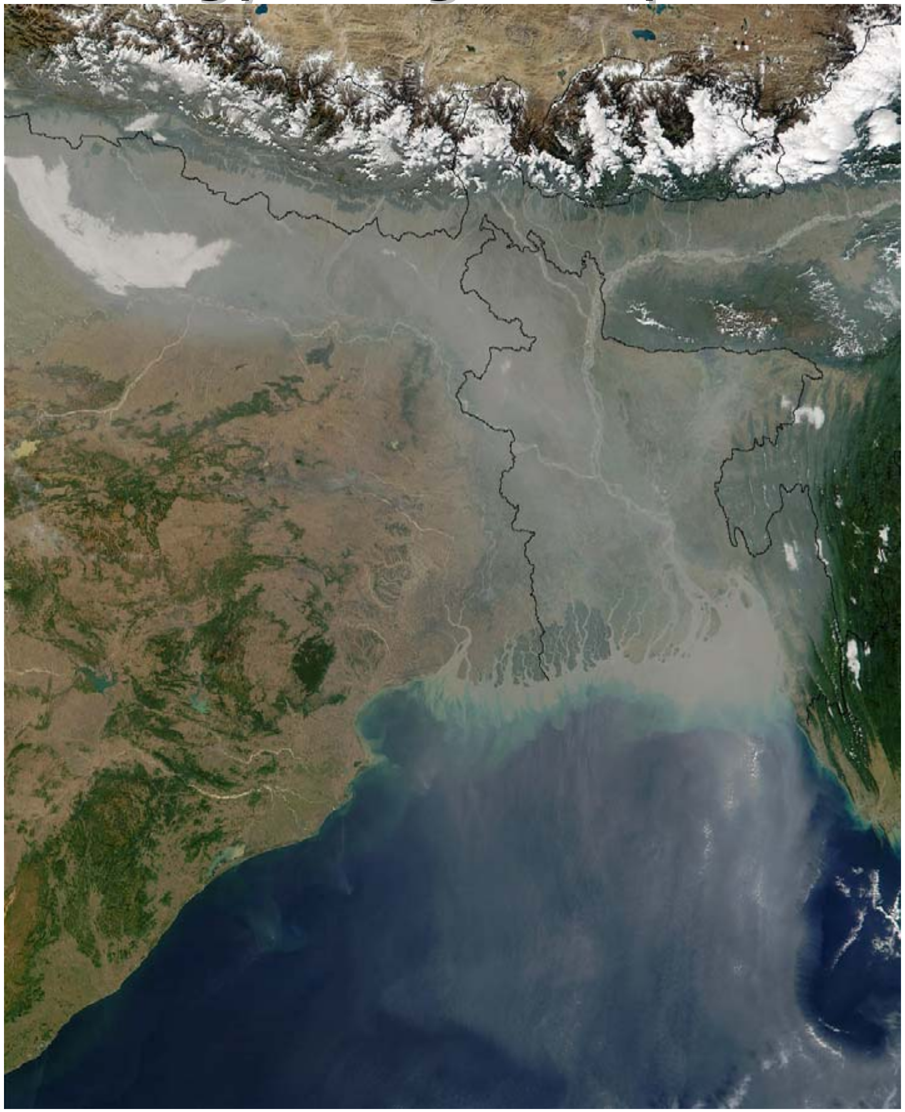
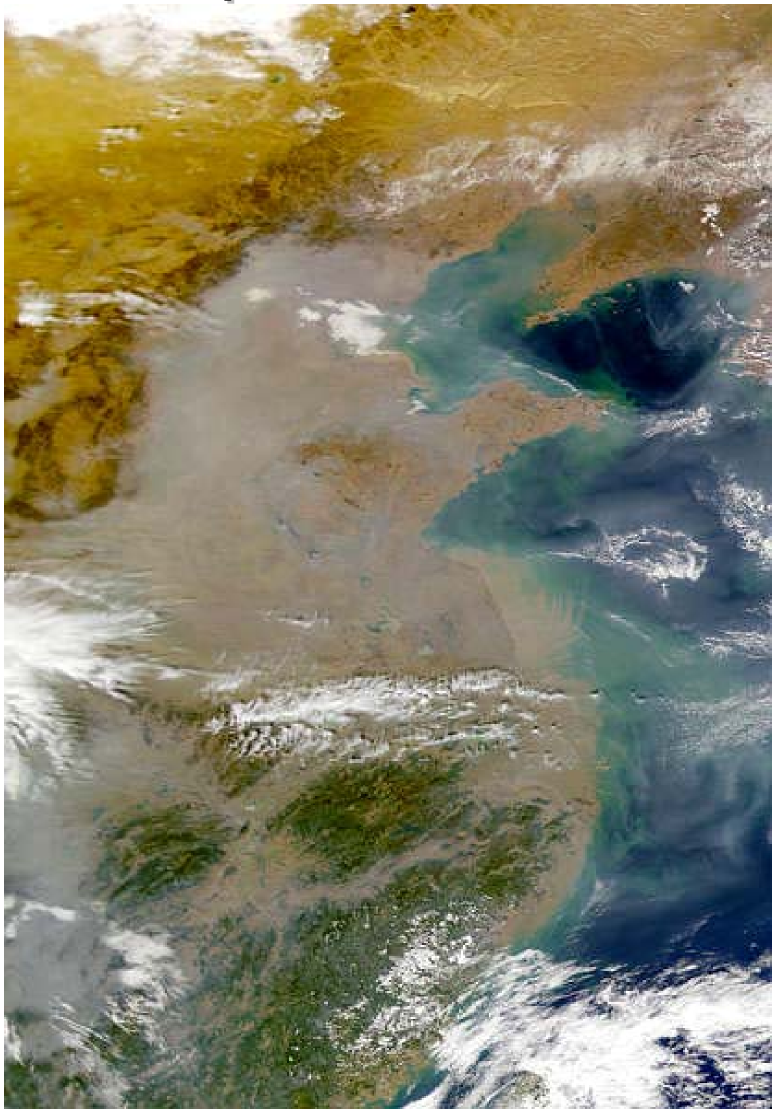
# Energy Budget Impacts of Atmospheric Aerosol




http://www.earth.nasa.gov

# Energy Budget Impacts of Atmospheric Aerosol





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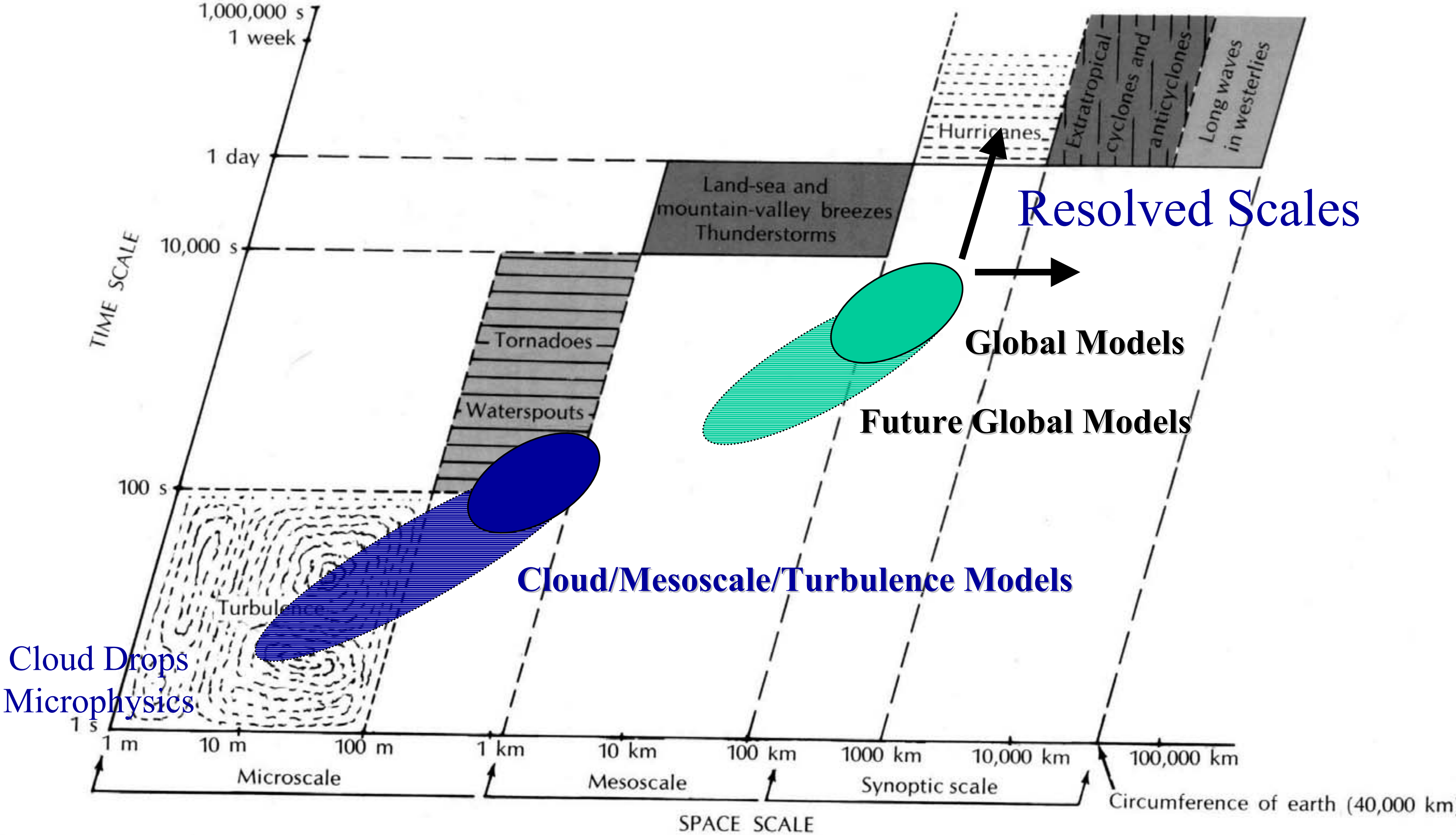
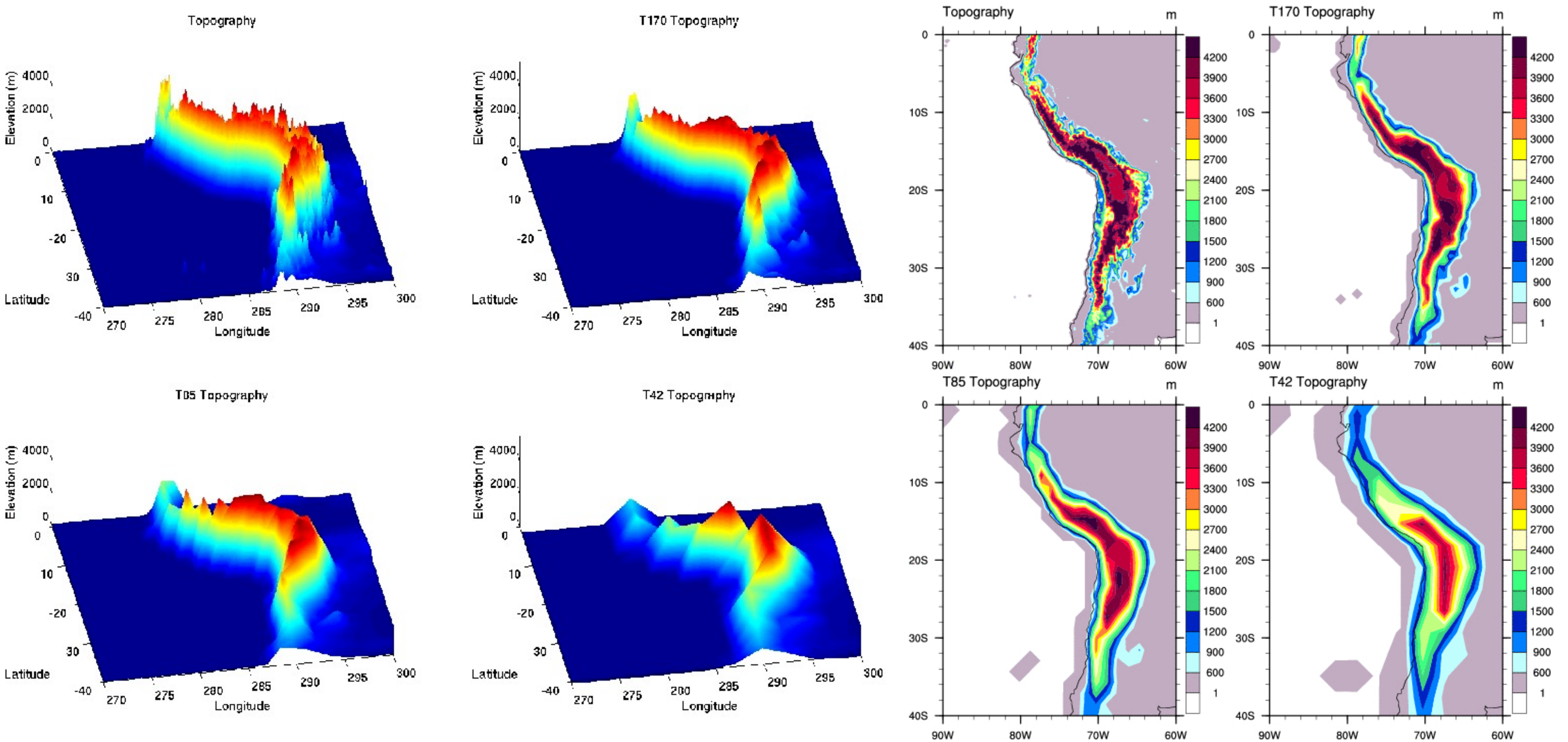
# Scales of Atmospheric Motions




*Anthes et al. (1975)*

# *Global Modeling and Horizontal Resolution*

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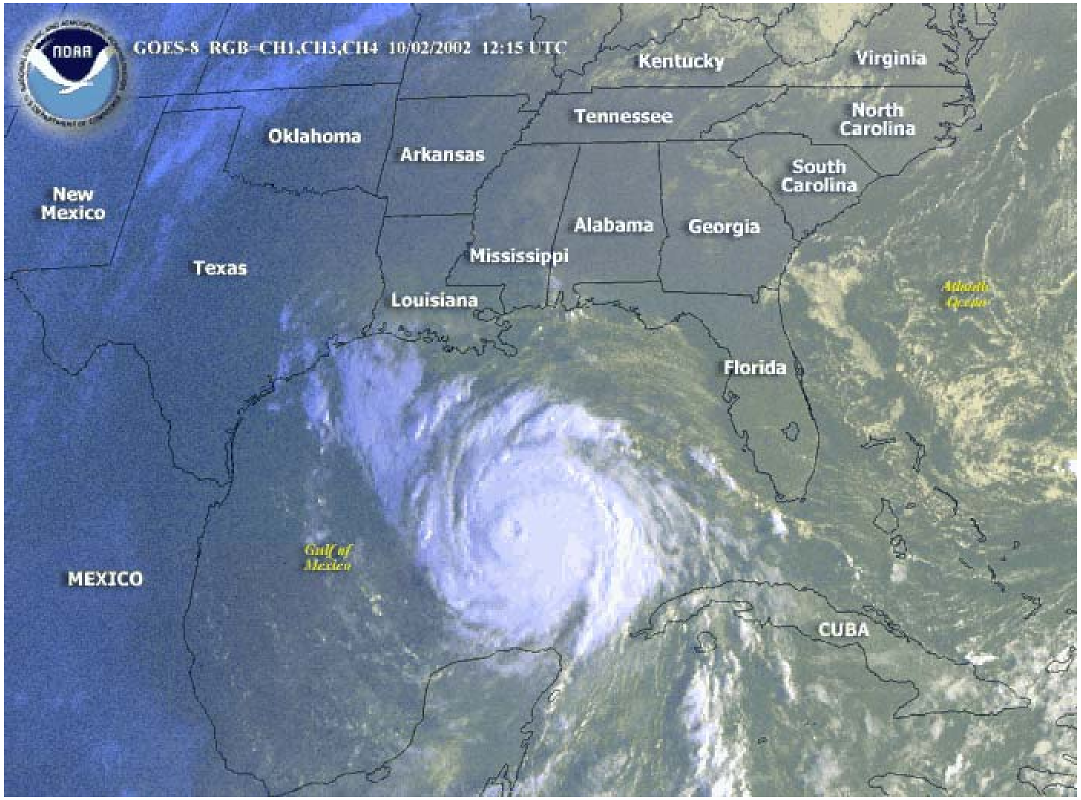
# *Capturing Principle Phenomenological Scales of Motion in Global Models*

Simulation of Tropical Cyclone Impacts on Climate




*Courtesy, Raymond Zehr, NOAA CIRA*

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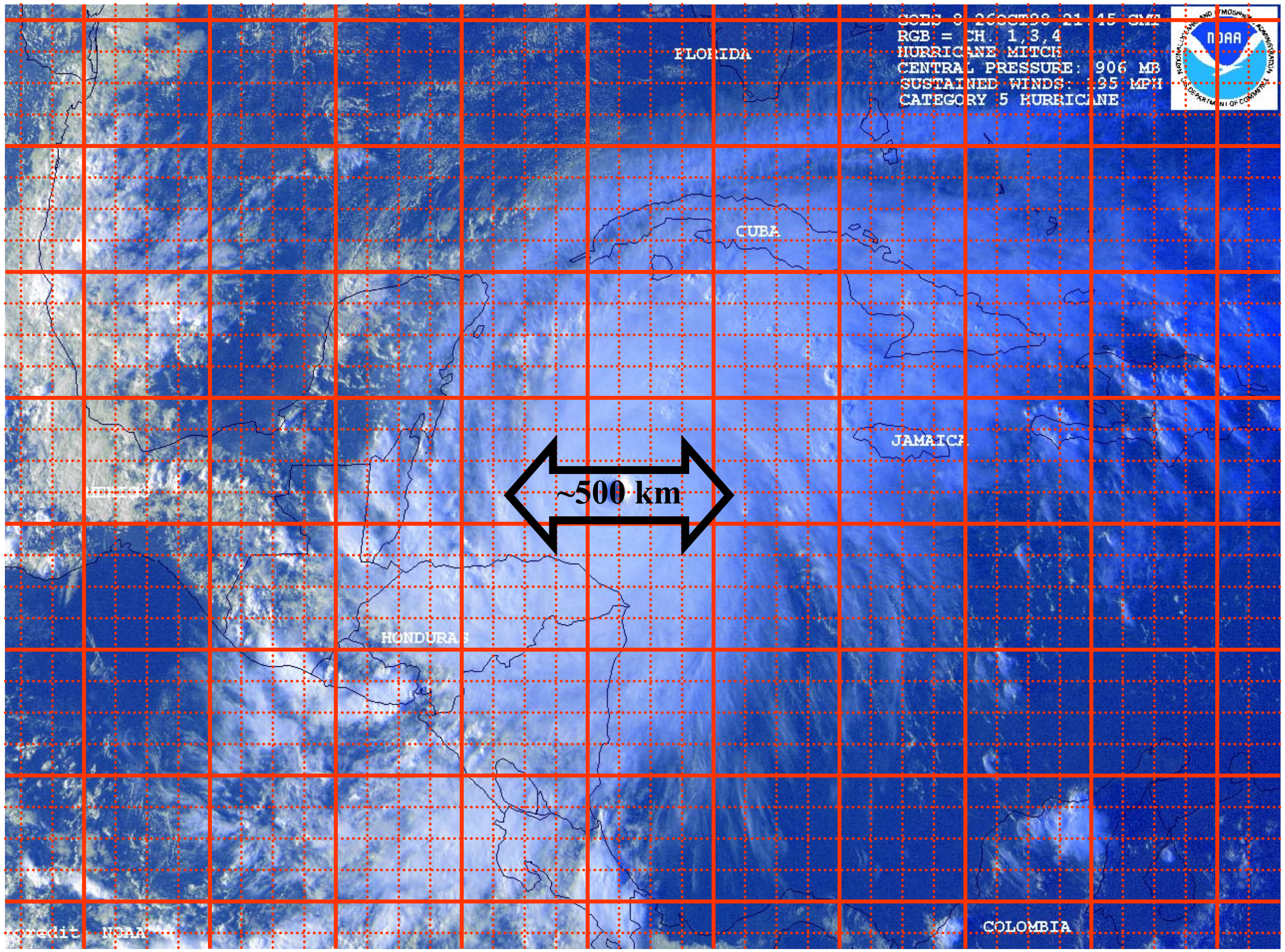
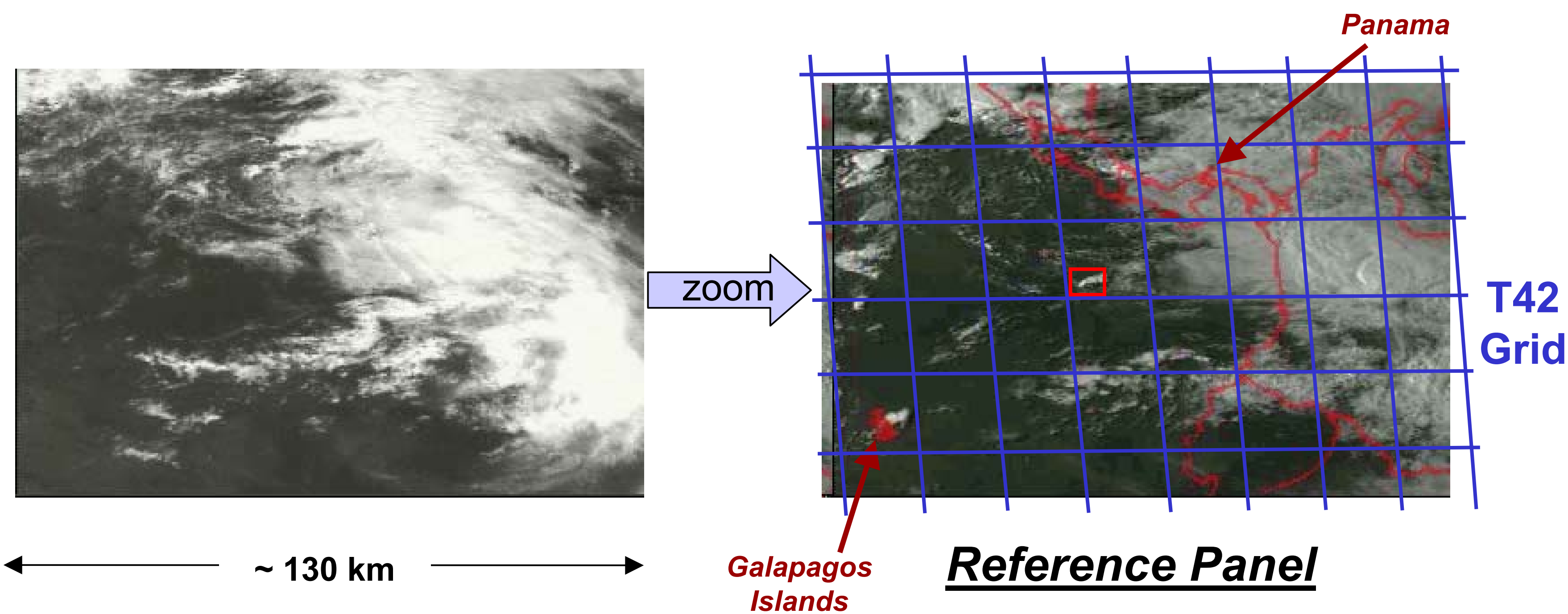
# *High-Resolution Global Modeling*

## Simulation of Tropical Cyclone Impacts on Climate



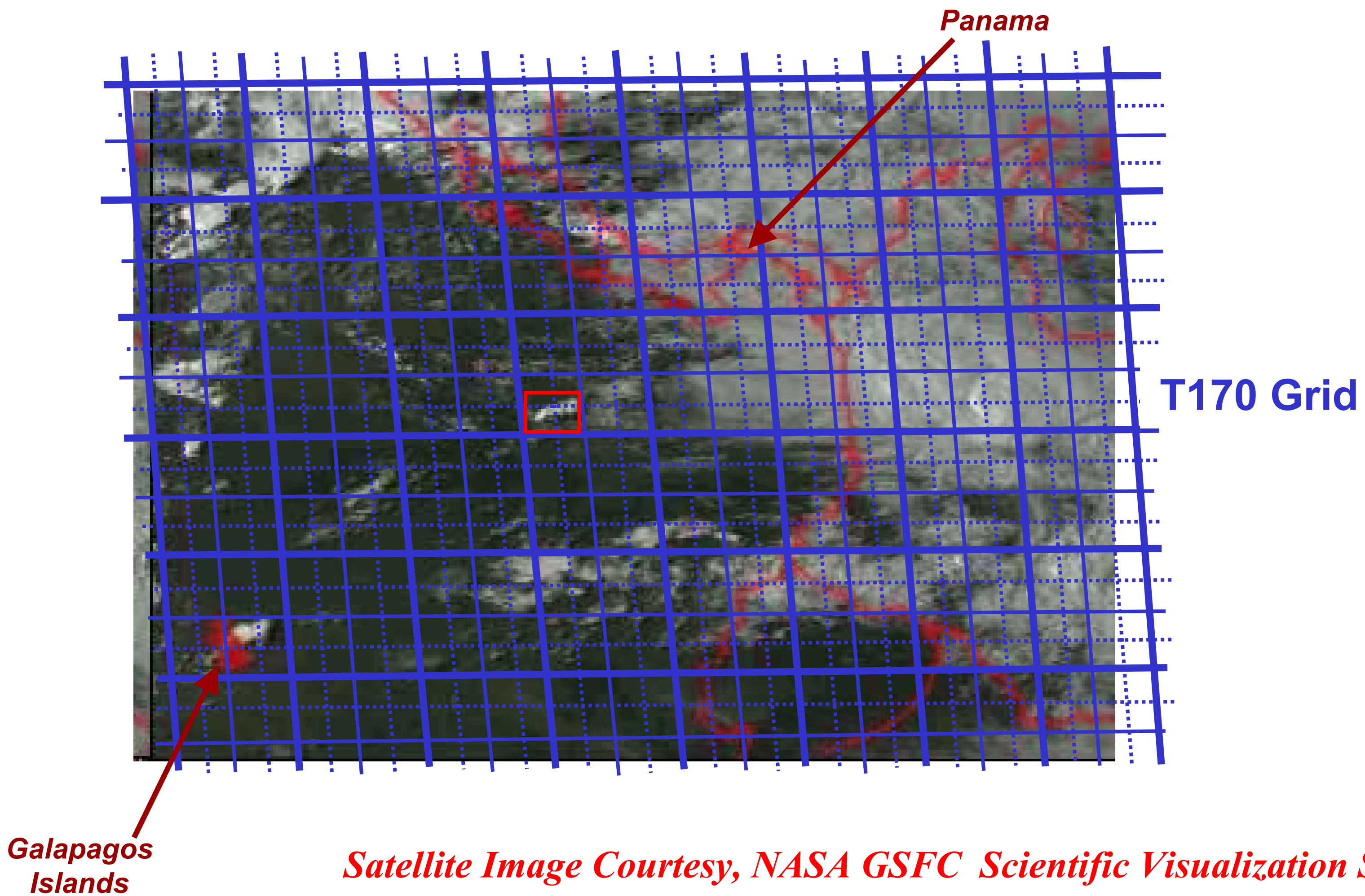
# High-Resolution Global Modeling

## Still a Need to Treat Subgrid-Scale Processes




*Courtesy, NASA Goddard Space Flight Center Scientific Visualization Studio*

# High-Resolution Global Modeling




Satellite Image Courtesy, NASA GSFC Scientific Visualization Studio

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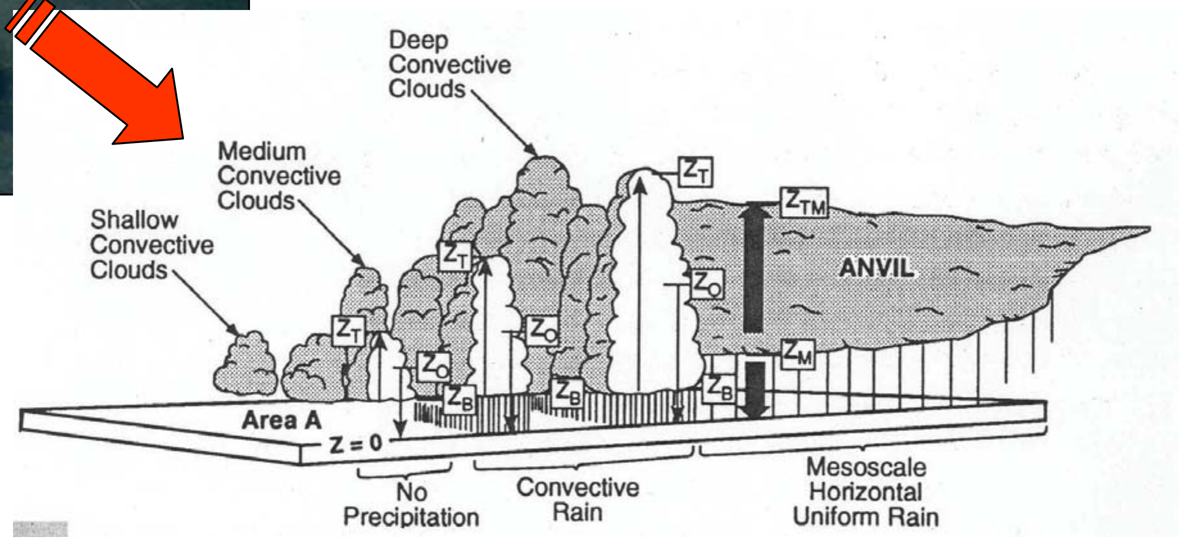
# Cumulus Convection

***If the atmosphere is buoyantly unstable to small vertical displacements, it can be said to be convectively unstable***

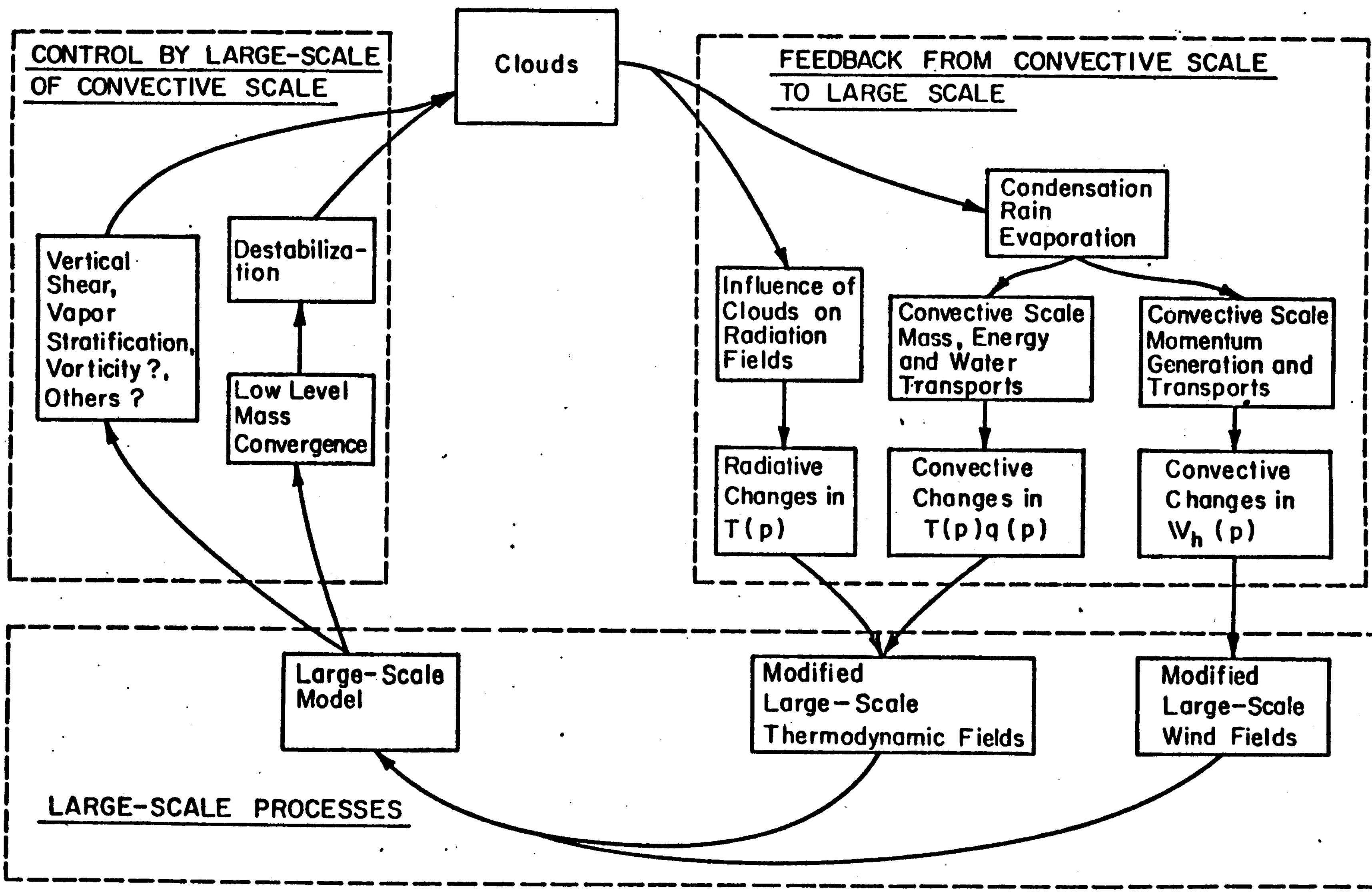
- Convective overturning
  - with or without phase change
  - space scale ~ 1-10km; time scale ~ 1 hour

- Moist convection
  - most common and energetically important
  - affects the general circulation on wide range of time scales
  - provides fundamental coupling of dynamics and hydrological cycle

# Process Models and Parameterization



# SIMPLIFIED LARGE-SCALE: CONVECTIVE INTERACTION



# Parameterization of Cumulus Convection

***To extract the details of how the observed profile is maintained by moist convection, it is necessary to use an abstraction for the collective behavior of convective motions***

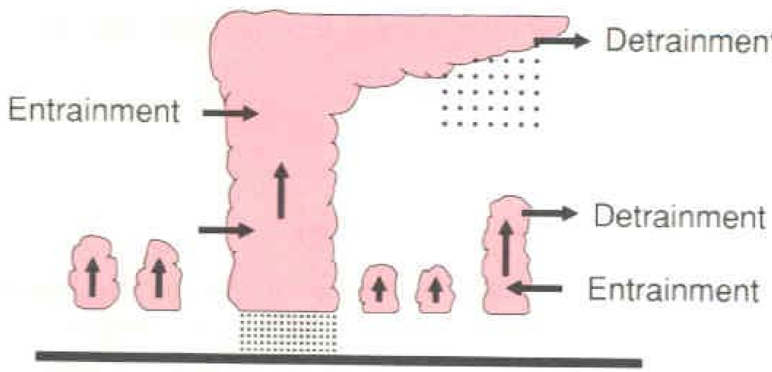
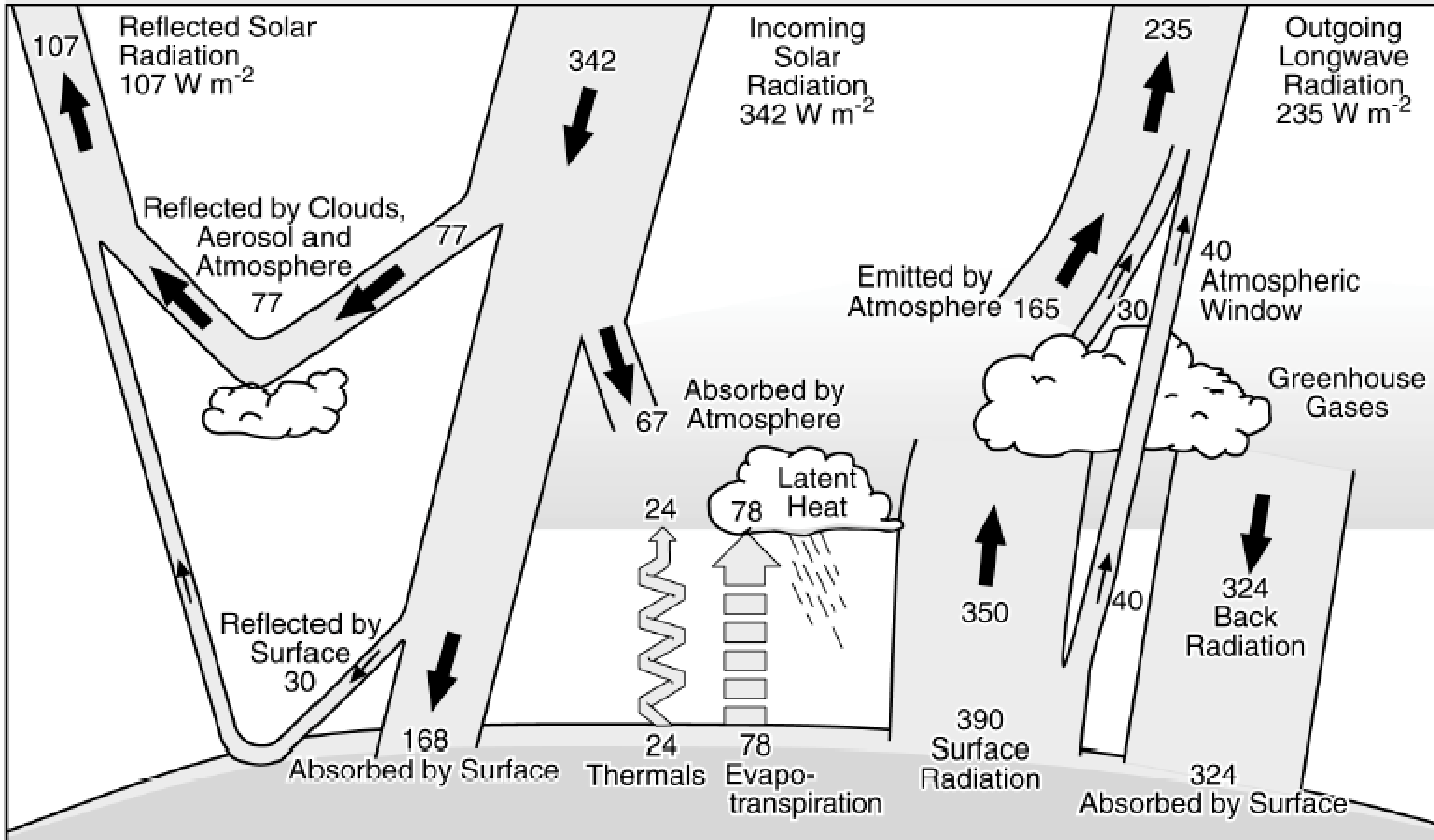



Fig. 10.16 Schematic of an ensemble of cumulus clouds. From Yanai et al. (1973).

- Convective mass flux
  - how much overturning is associated with convective activity
- Breakdown of total diabatic forcing
  - where is the water condensing and/or raining out
  - what role do the convective eddy transports play

# What are the key uncertainties?

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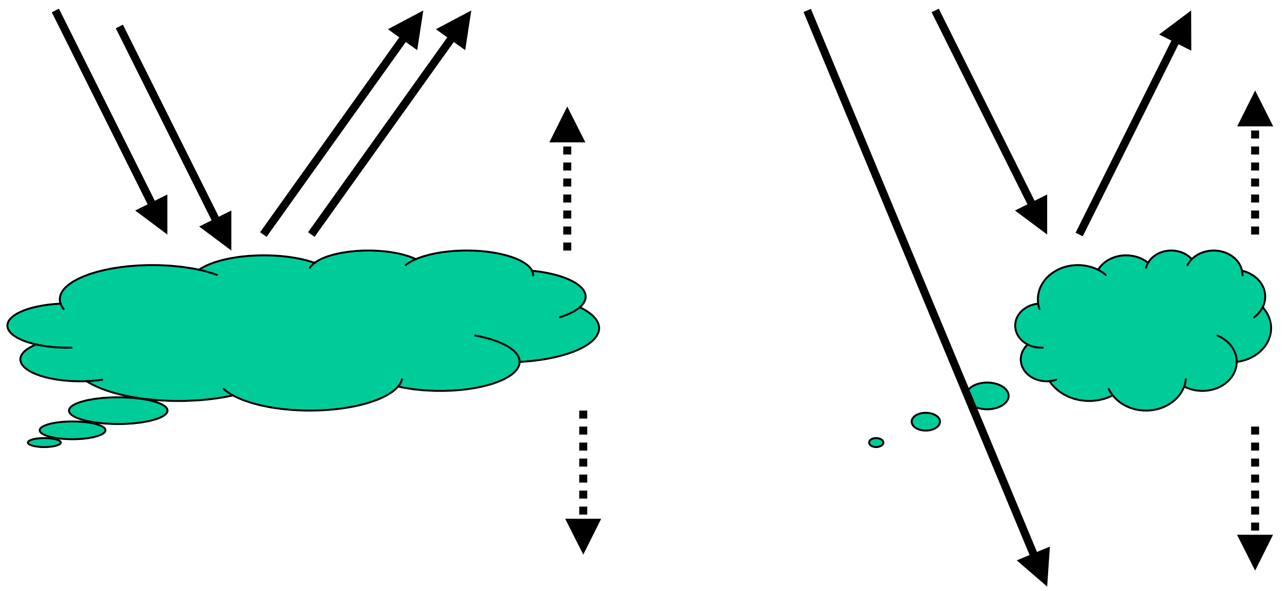
# Uncertainties (1):

- Low Clouds over the ocean:
  Reflect Sunlight (cool) : Dominant Effect
  Trap heat (warm)



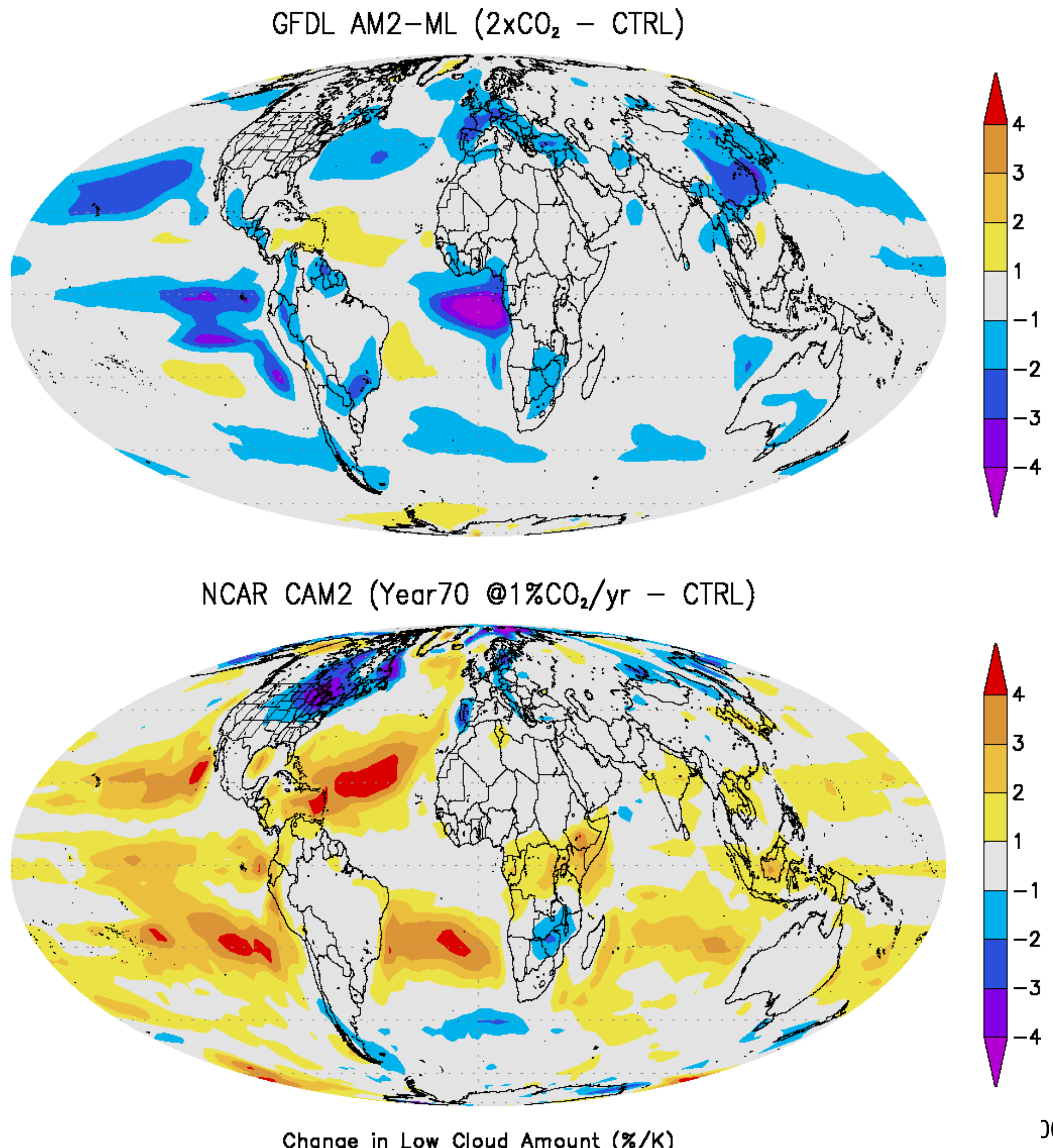
More Clouds=Cooling

Fewer Clouds=Warming

# Marine Stratus: Low Clouds over the Ocean

# Low Clouds Over the Ocean

2 Models: Changes are OPPOSITE!

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# Parameterization of Clouds

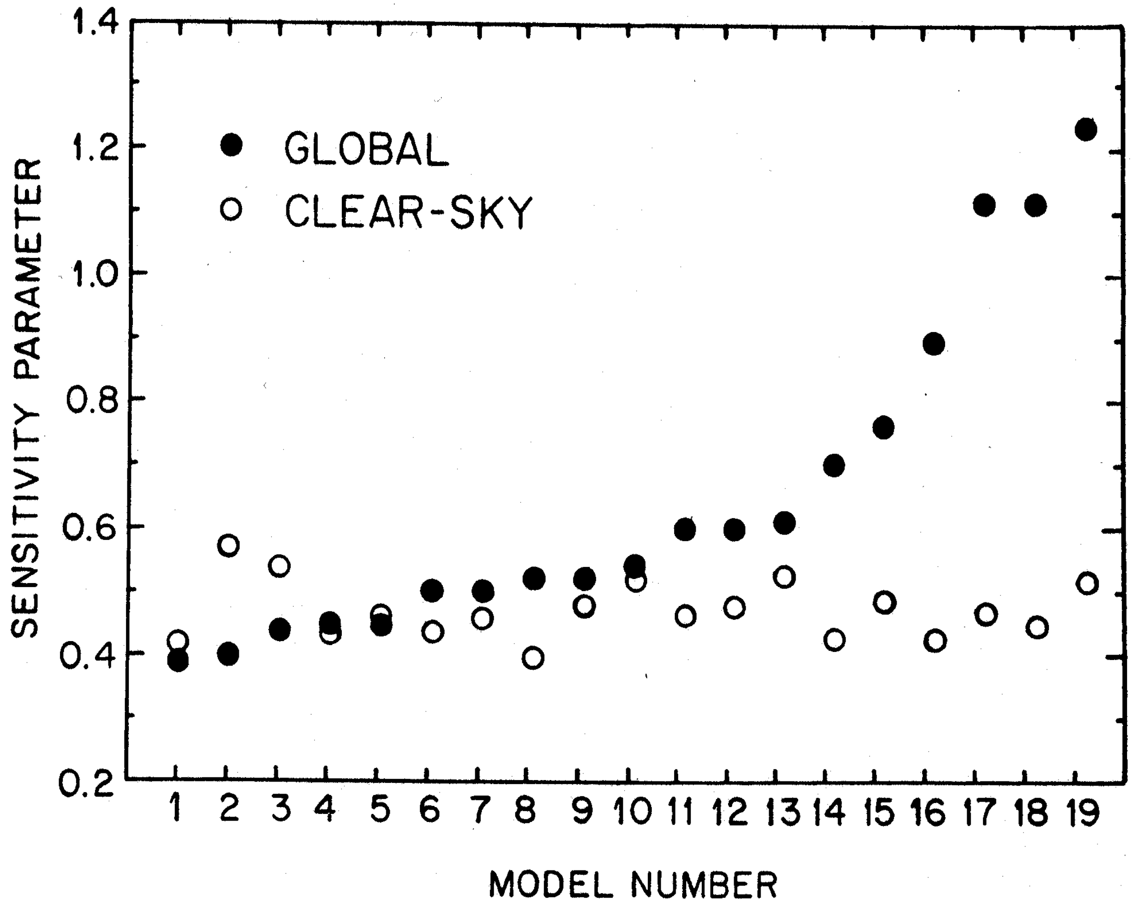
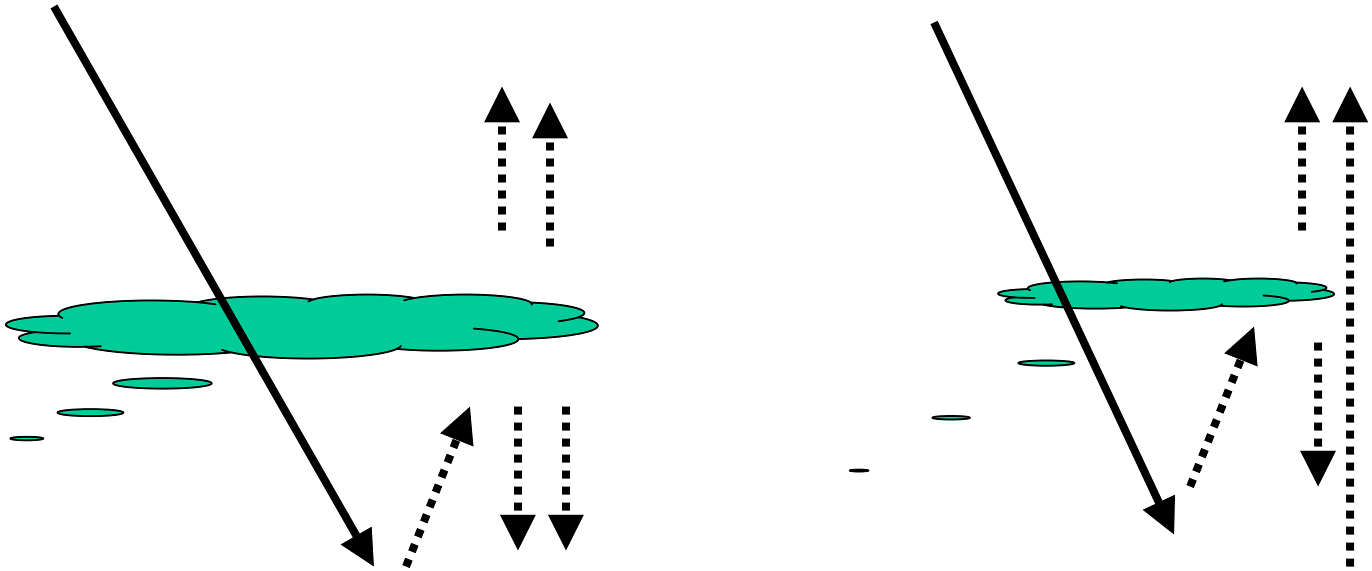



Fig. 1. Clear-sky and global sensitivity parameters (K $m^2$ $W^{-1}$) for the 19 GCMs. The model numbers correspond to the ordering in Table 9.

Cess et al. (1990)

# Uncertainties (2):

2. High Clouds:
   Dominant effect is that they Trap heat (warm)



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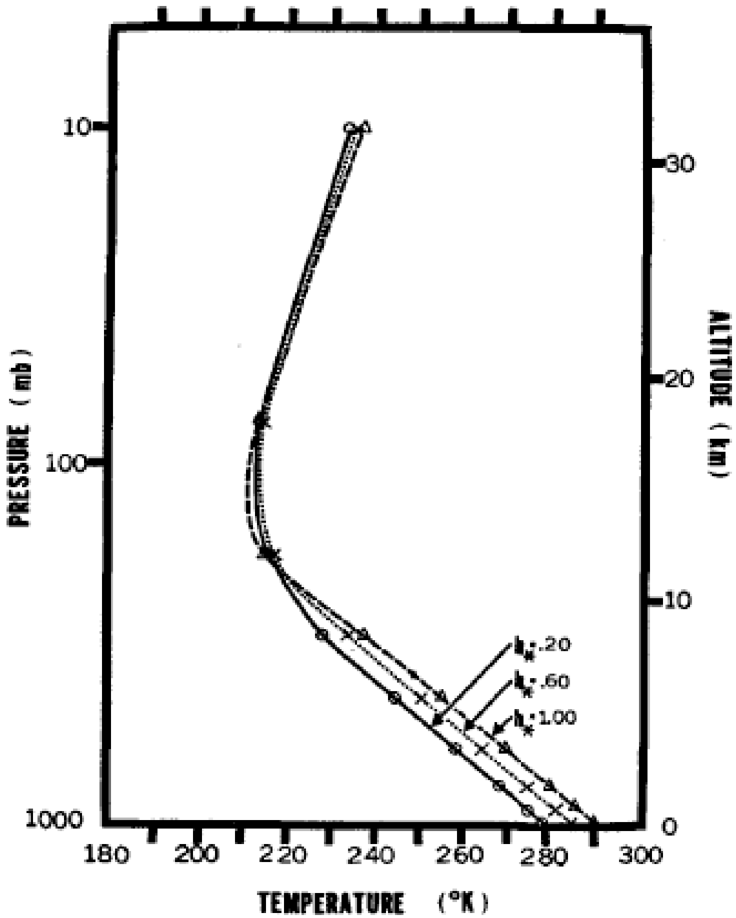
# Uncertainties (3):

- Water Vapor: largest greenhouse gas
  Increasing Temp=Increasing water Vapor (more greenhouse)
  Effect is expected to 'amplify' warming through a 'feedback'




1D Radiative-Convective Model:
Higher humidity=>warmer surface

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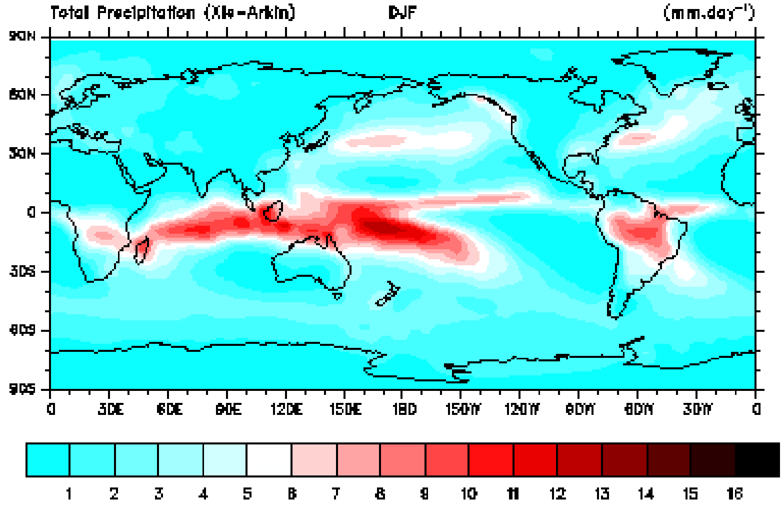
# How can we evaluate simulation quality?

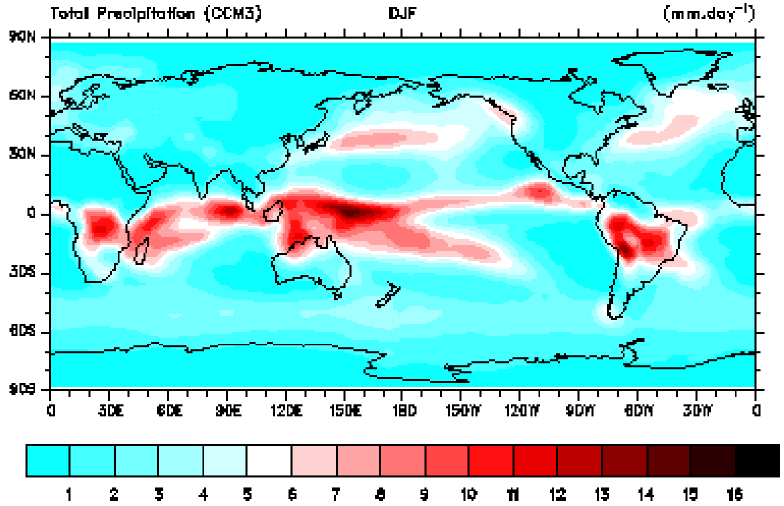
- Continue to compare long term mean climatology
  - average mass, energy, and momentum balances
  - tells you where the physical approximations take you
    - ***but you don't necessarily know how you get there!***
- Must also consider dominant modes of variability
  - provides the opportunity to evaluate *climate sensitivity*
    - response of the climate system to a specific forcing factor
  - evaluate modeled response on a hierarchy of time scales
  - exploit natural forcing factors to test model response
    - diurnal and seasonal cycles
    - El Niño Southern Oscillation (ENSO)
    - intraseasonal variability; e.g., MJO
    - solar variability
    - volcanic aerosol loading

# Comparison of Mean Simulation Properties

Observed Precipitation




Simulated Precipitation

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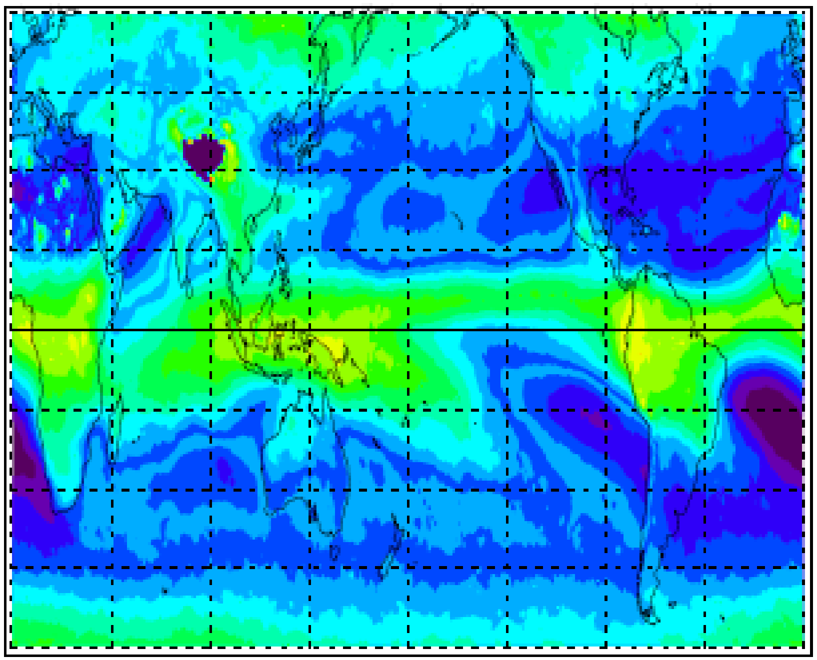
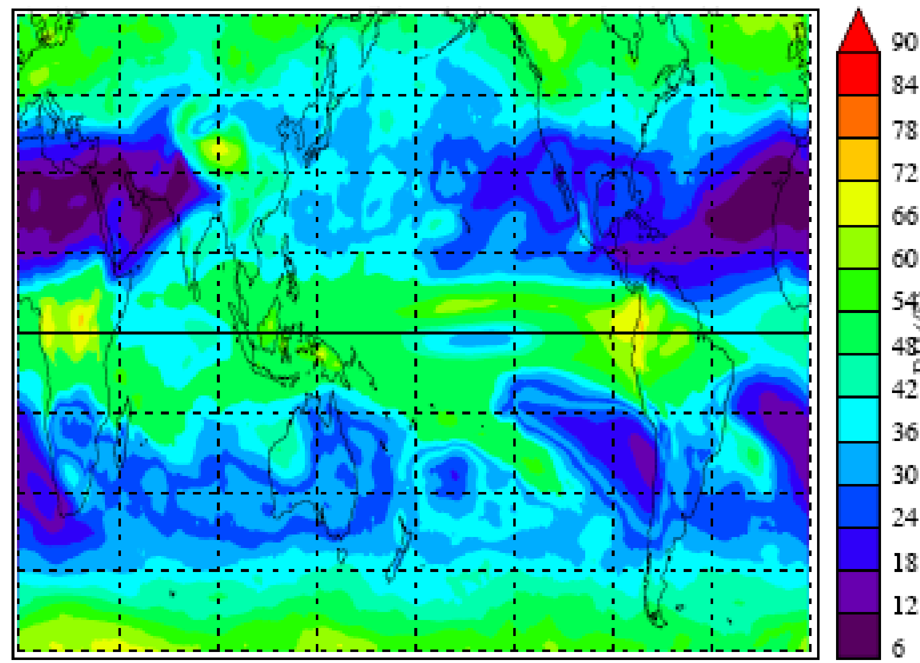
# Mean Biases

## Relative humidity, March-May 3km (9,000ft)

### Observed



### Simulated



# Variability: El Niño Composite

Observed

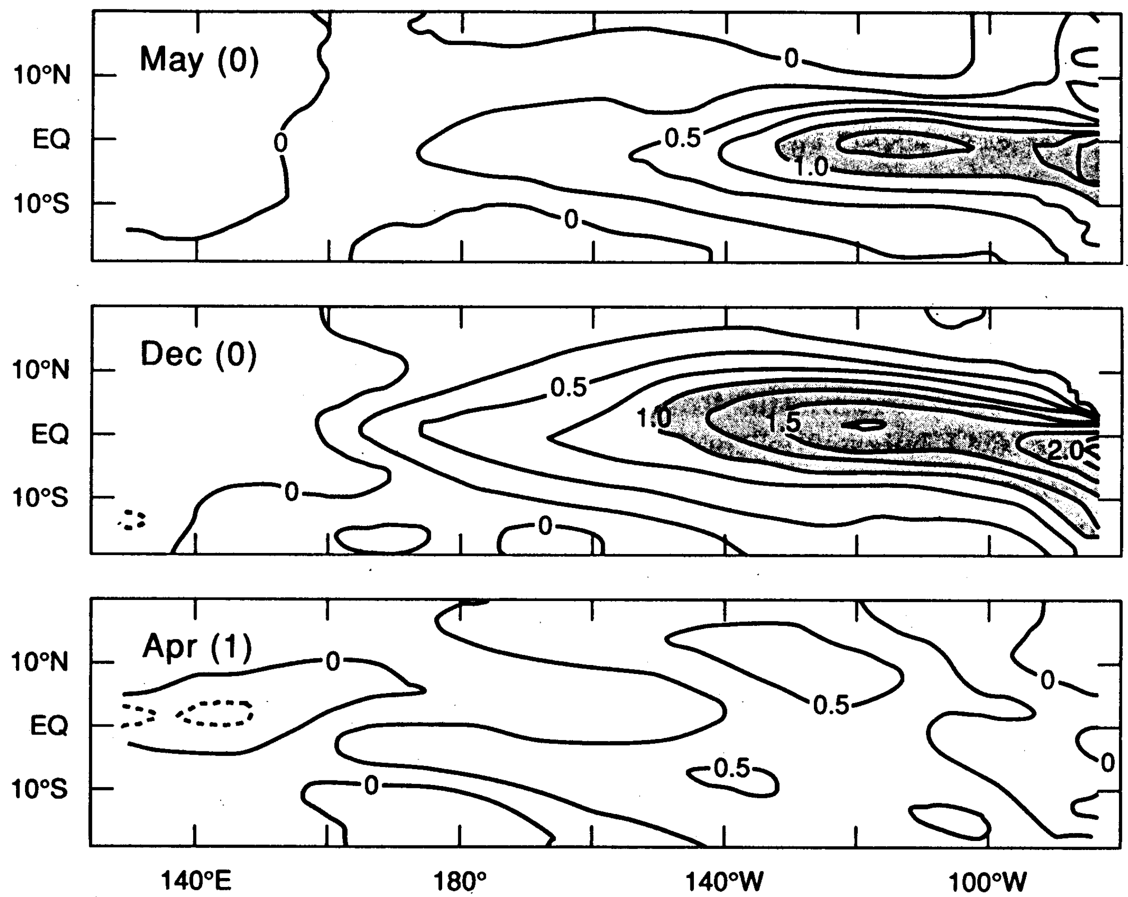
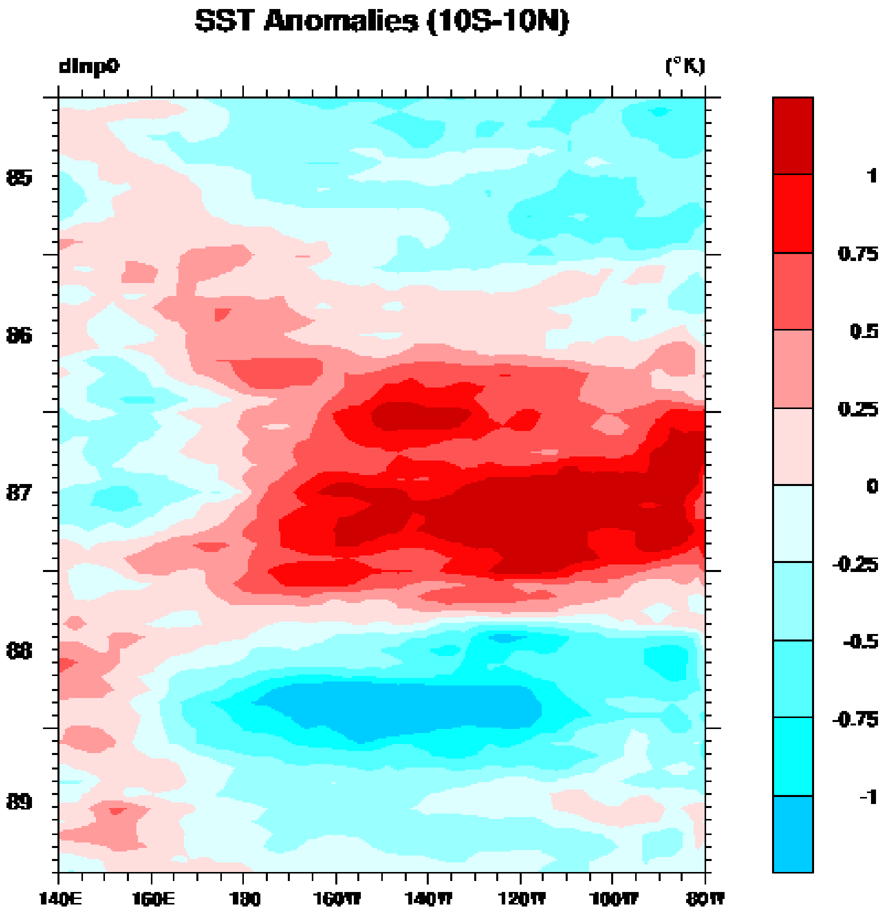



Fig. 18.2 Sea surface temperature anomalies (°C) for a composite El Niño (Rasmusson and Carpenter, 1982), constructed by averaging over 6 events (1951, 1953, 1957, 1965, 1969, 1972; cf. Fig. 18.1). Shown are maps for May and December of the El Niño year and April of the following year.

# Testing AGCM Sensitivity

Simulated

***Pacific SST Anomalies and ENSO***




Hack (1998)

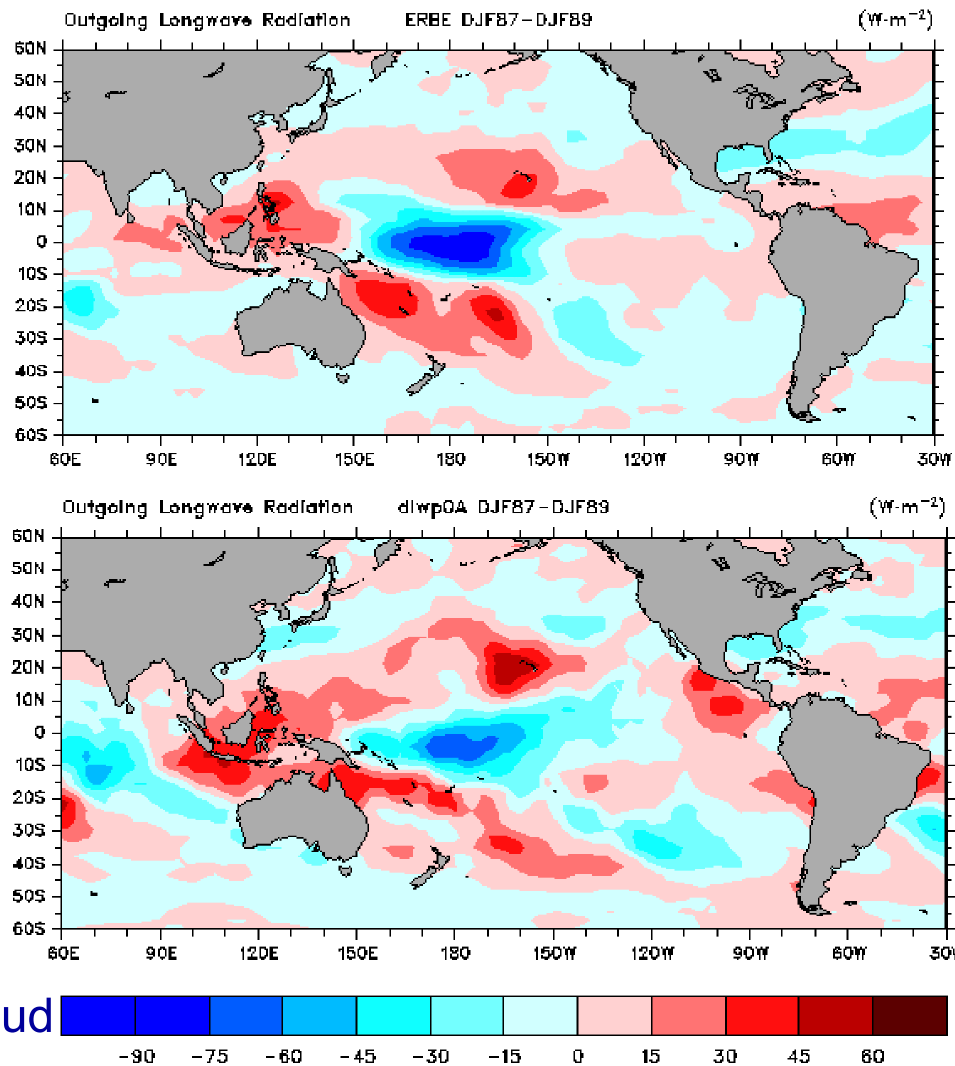
NCAR

# Testing AGCM Sensitivity

## *Cloud (OLR) Anomalies and ENSO*

Observed

Simulated




More Cloud

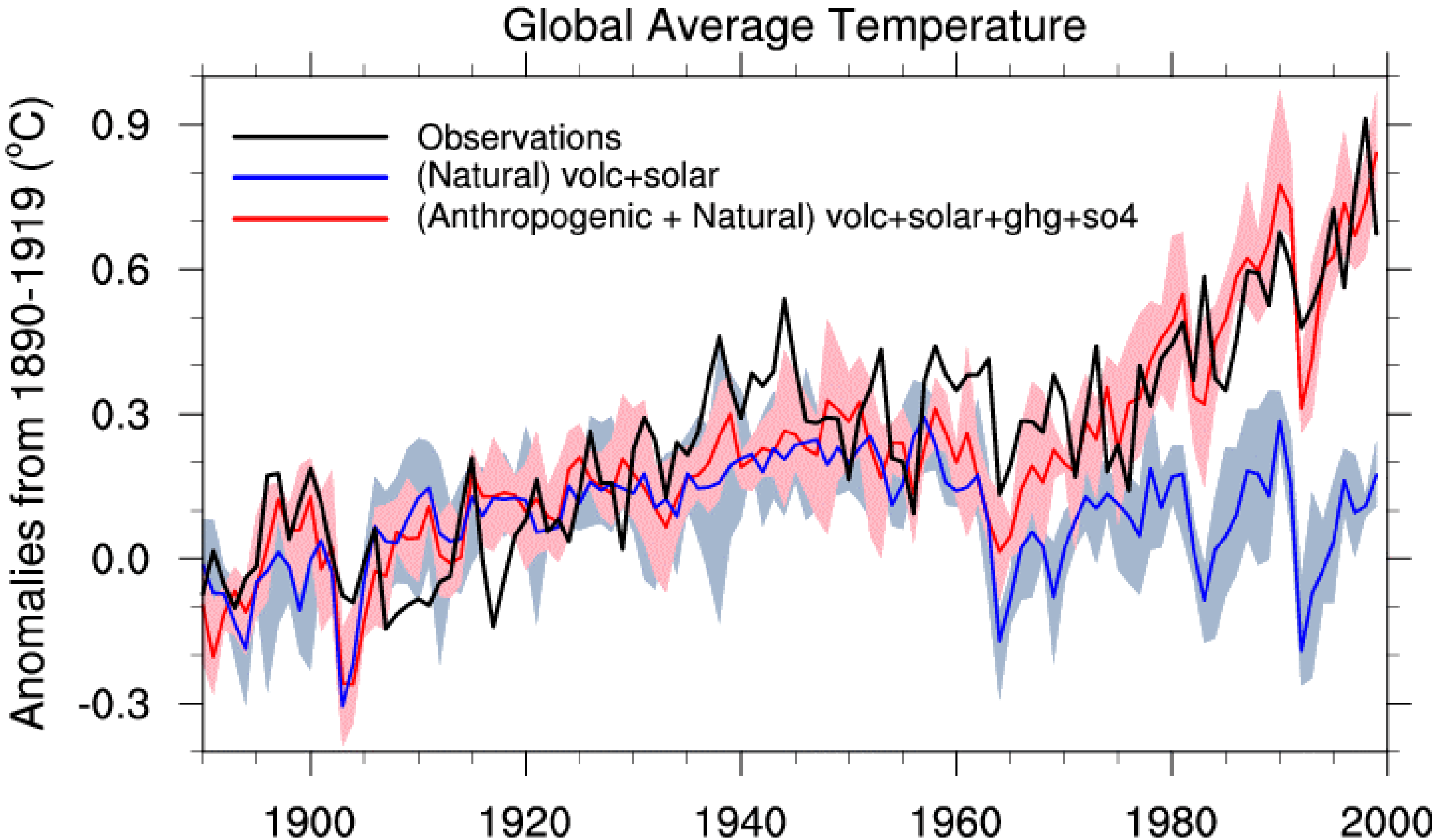
Less Cloud

Hack (1998)

NCAR

# *Observations: 20th Century Warming*

## Model Solutions with Human Forcing




NCAR

J. J. Hack/A. Gettelman: June 2005

# Improving simulation quality

- Examine role of parameterization techniques on transient behavior
  - oversimplifications playing a role in inadequate variability?
- Understand role of scale interaction on transient and mean state

***CCM2 ITCZ behavior as function of horizontal resolution***

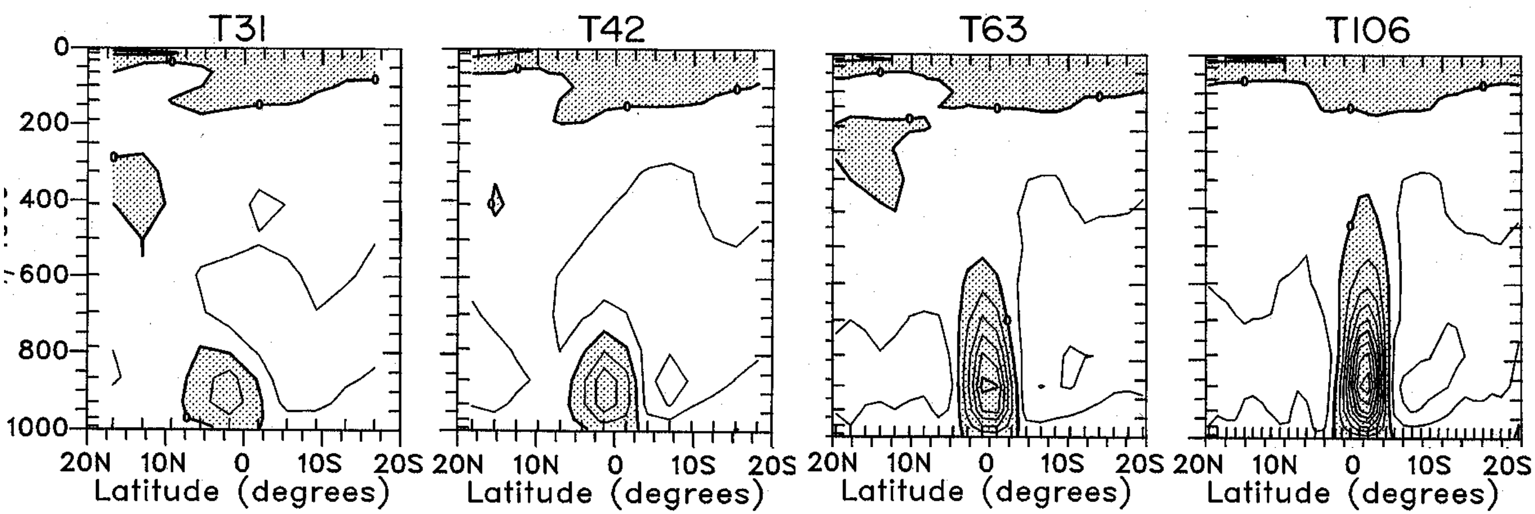
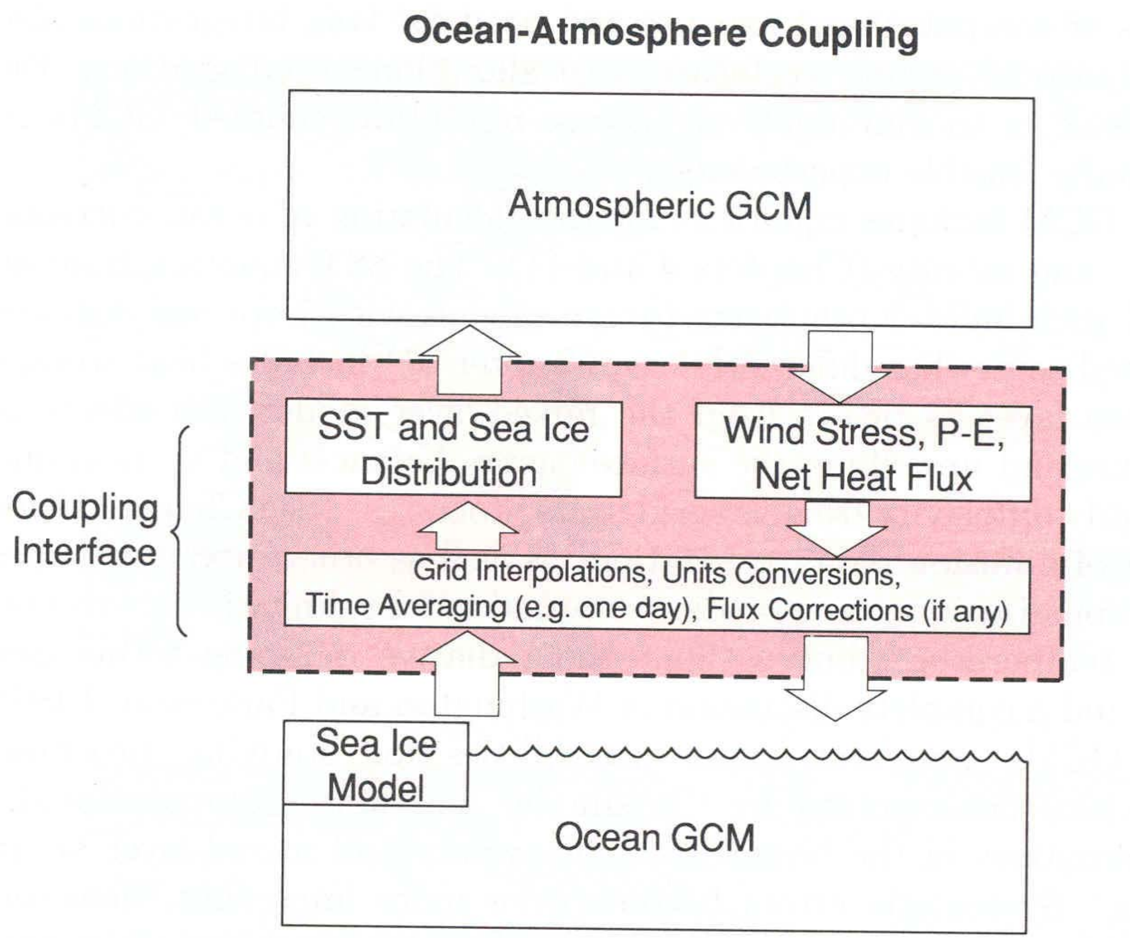



**Fig. 6.** January average, zonal average over Atlantic (30°W to 7.5°E) pressure vertical velocity ($\omega$) for R15, T21, T31, T42, T63, and T106 simulations. Contour interval is 20 mb day$^{-1}$, negative (upward) regions *stippled*

Williamson, Kiehl, and Hack (1995)

NCAR

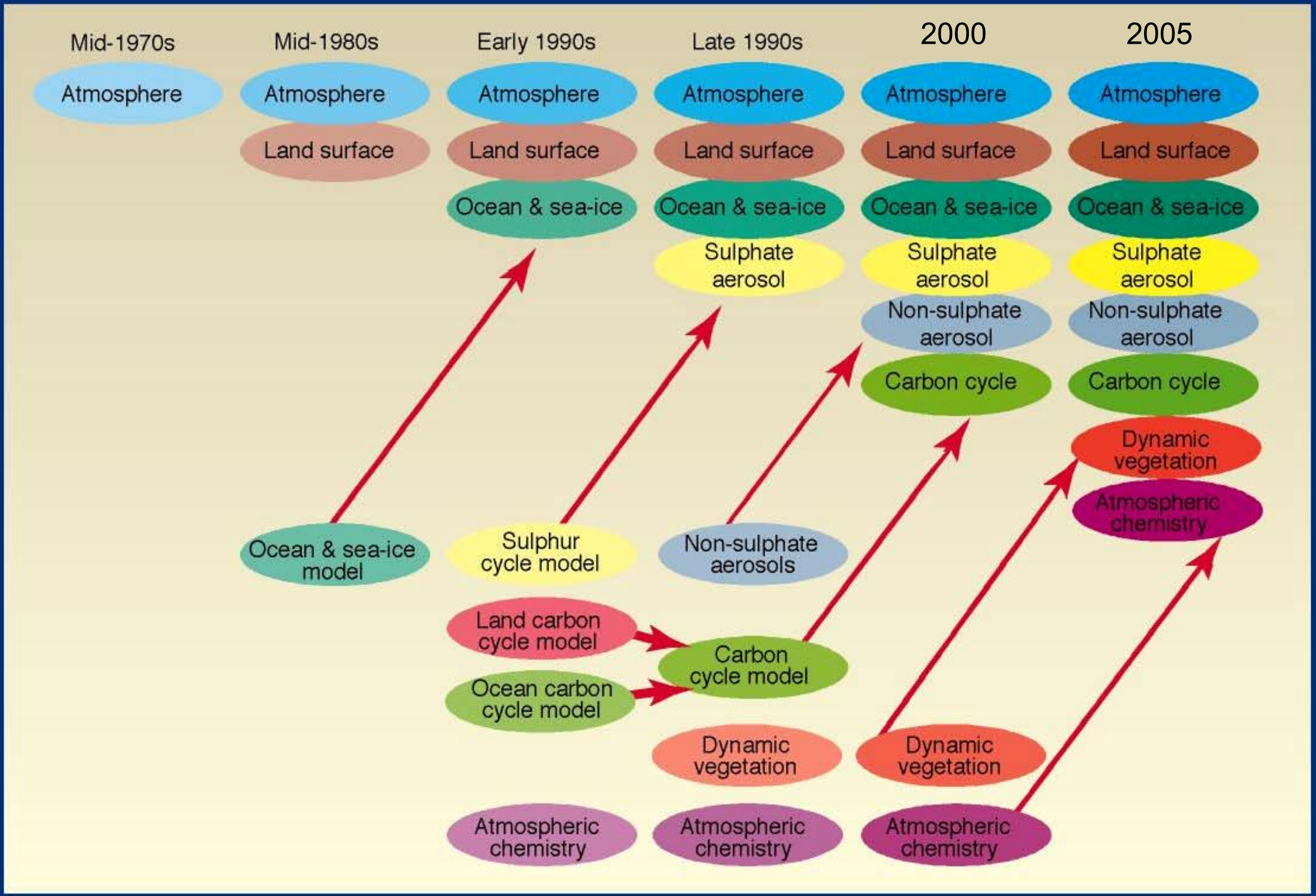
# Coupled Models = Increased Technical Complexity




Note: Ocean GCM's are as complex as Atmosphere GCM's!

# Climate Model 'Evolution'

## The development of climate models, past, present and future




WG1 - TS BOX 3
FIGURE 1

# Summary

- Global Climate Modeling
  - complex and evolving scientific problem
  - parameterization of physical processes pacing progress
  - observational limitations pacing process understanding
- Parameterization of physical processes
  - opportunities to explore alternative formulations
    - exploit higher-order statistical relationships?
  - exploration of scale interactions using modeling and observation
    - high-resolution process modeling to supplement observations
      - e.g., identify optimal truncation strategies for capturing major scale interactions
    - better characterize statistical relationships between resolved and unresolved scales

# The End