An Introduction to Climate Modeling

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Selected overheads by Doug Nychka

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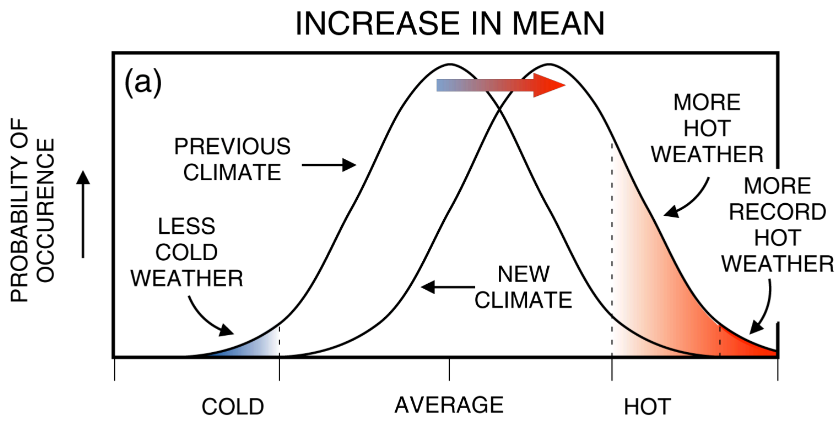
Outline

- 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
- 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?

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



(1) What is Climate?

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

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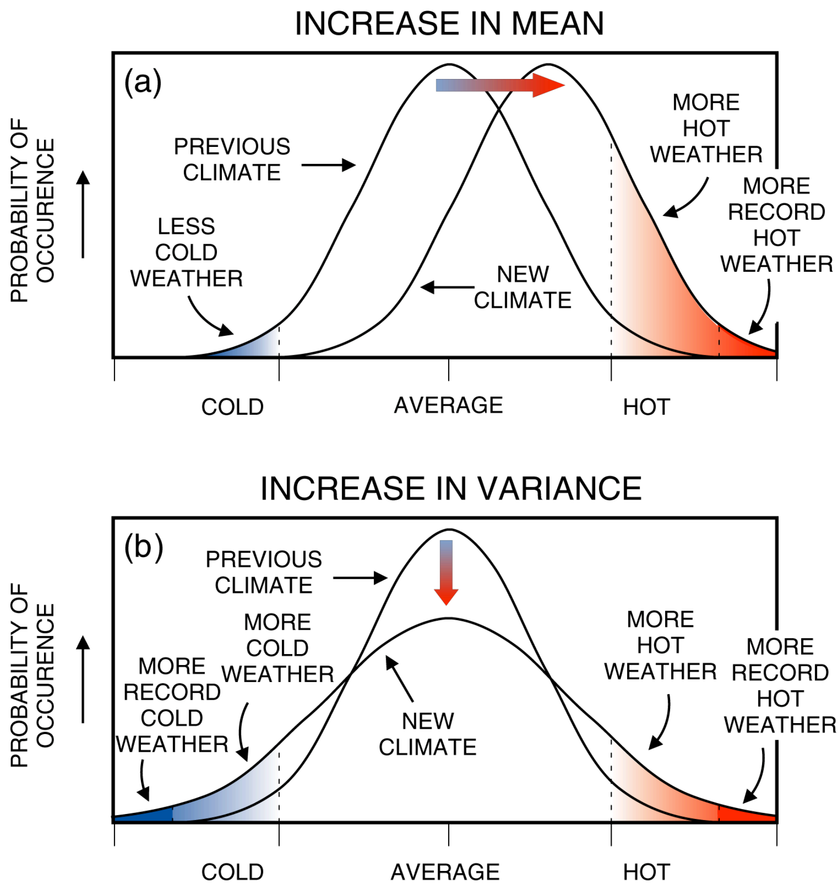

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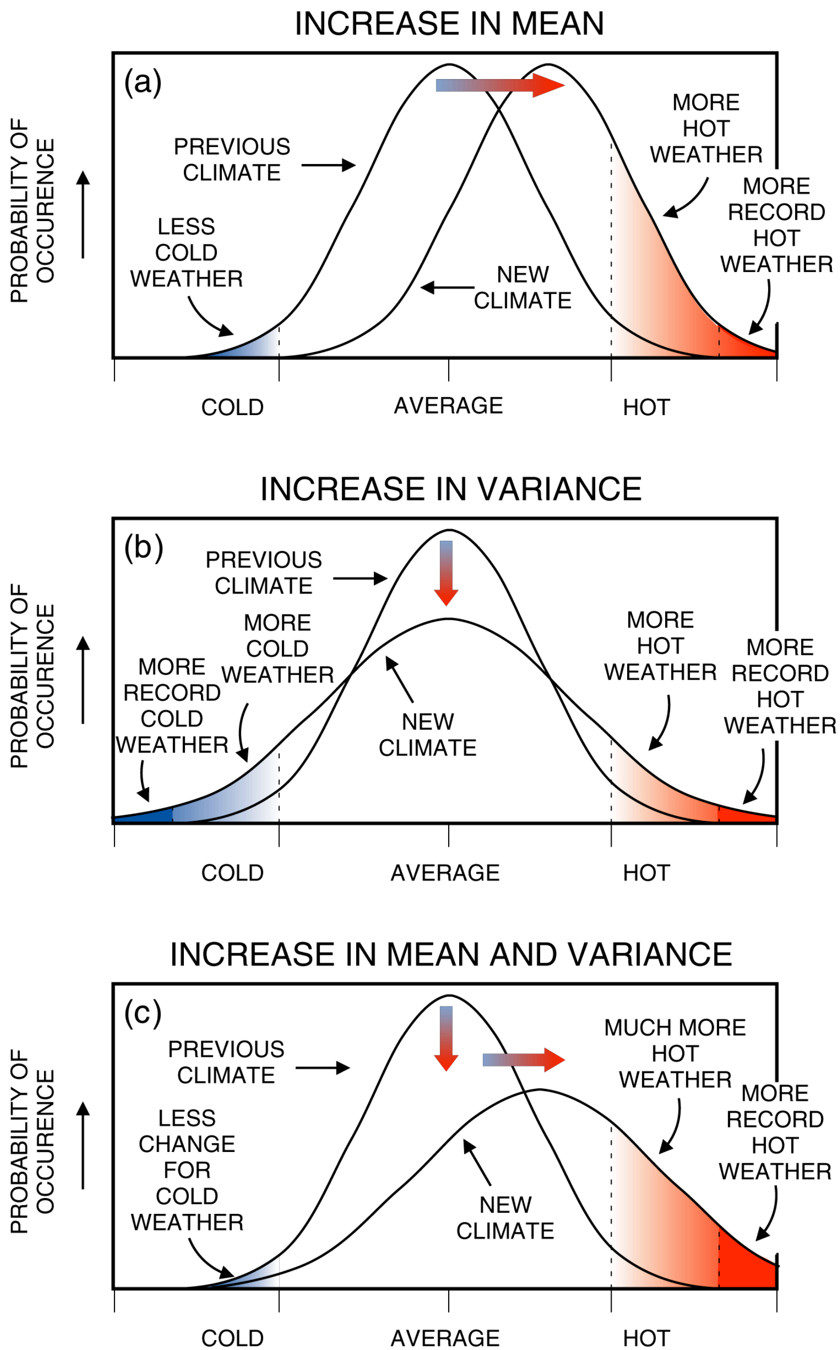
Climate change and its manifestation in terms of weather (climate extremes)



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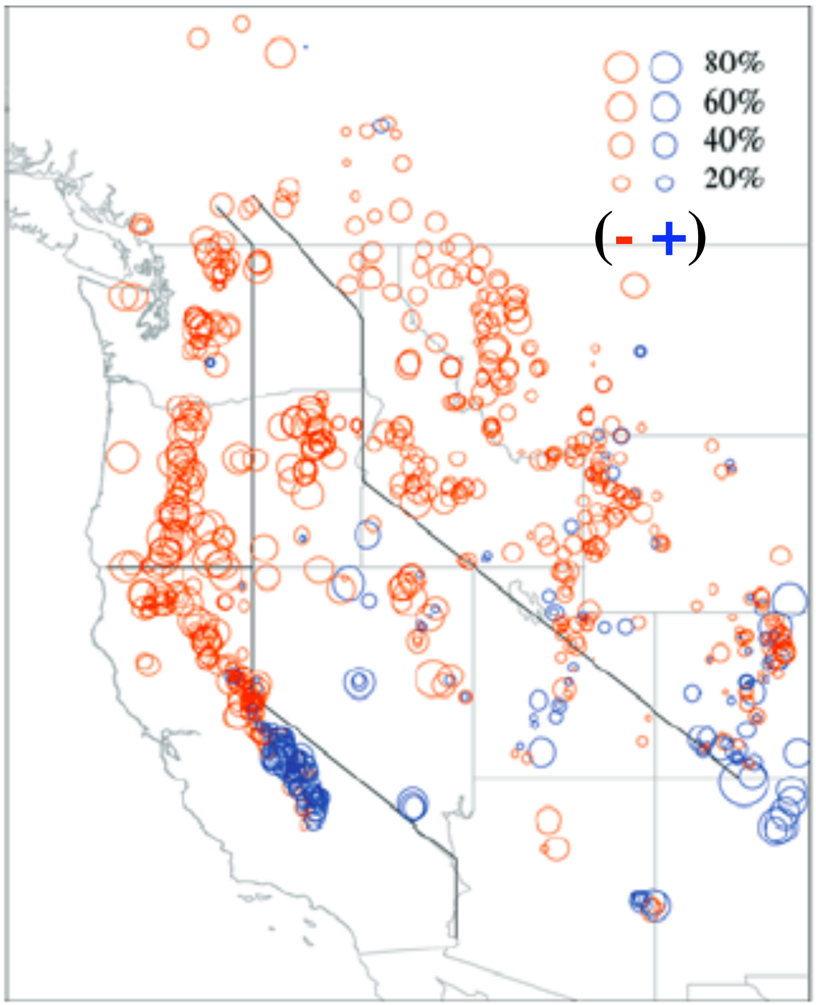
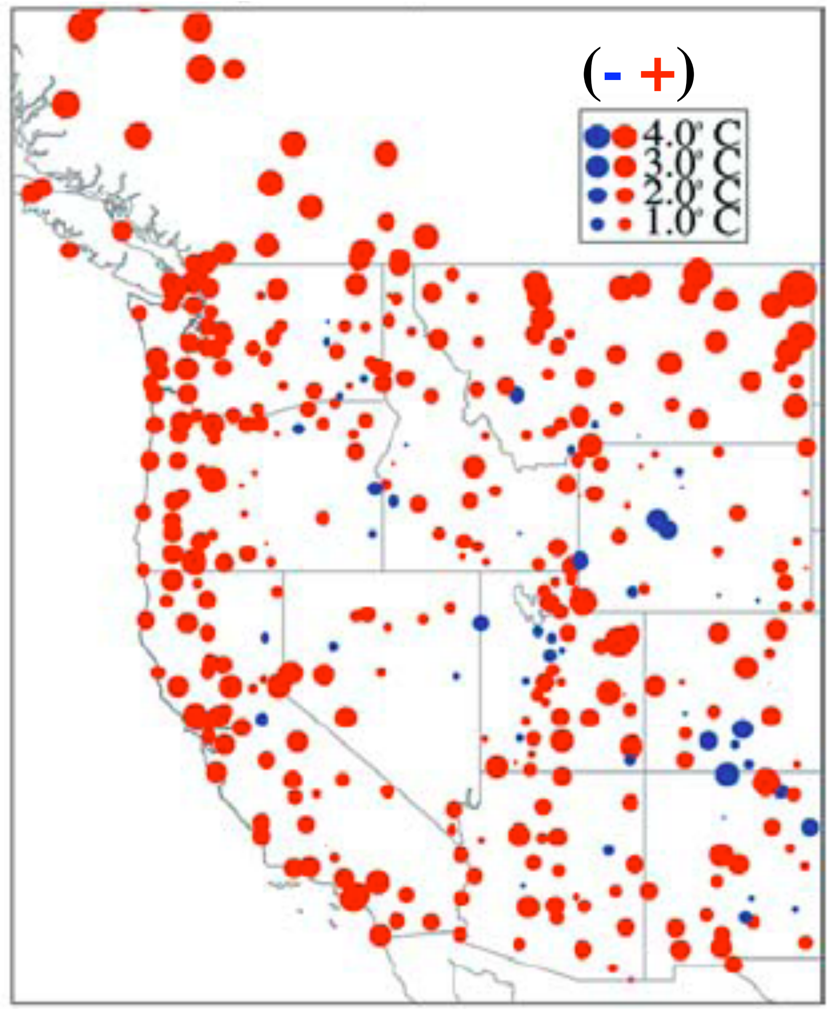
Impacts of Climate Change

Observed Change 1950-1997

Snowpack



Temperature



Mote et al 2005

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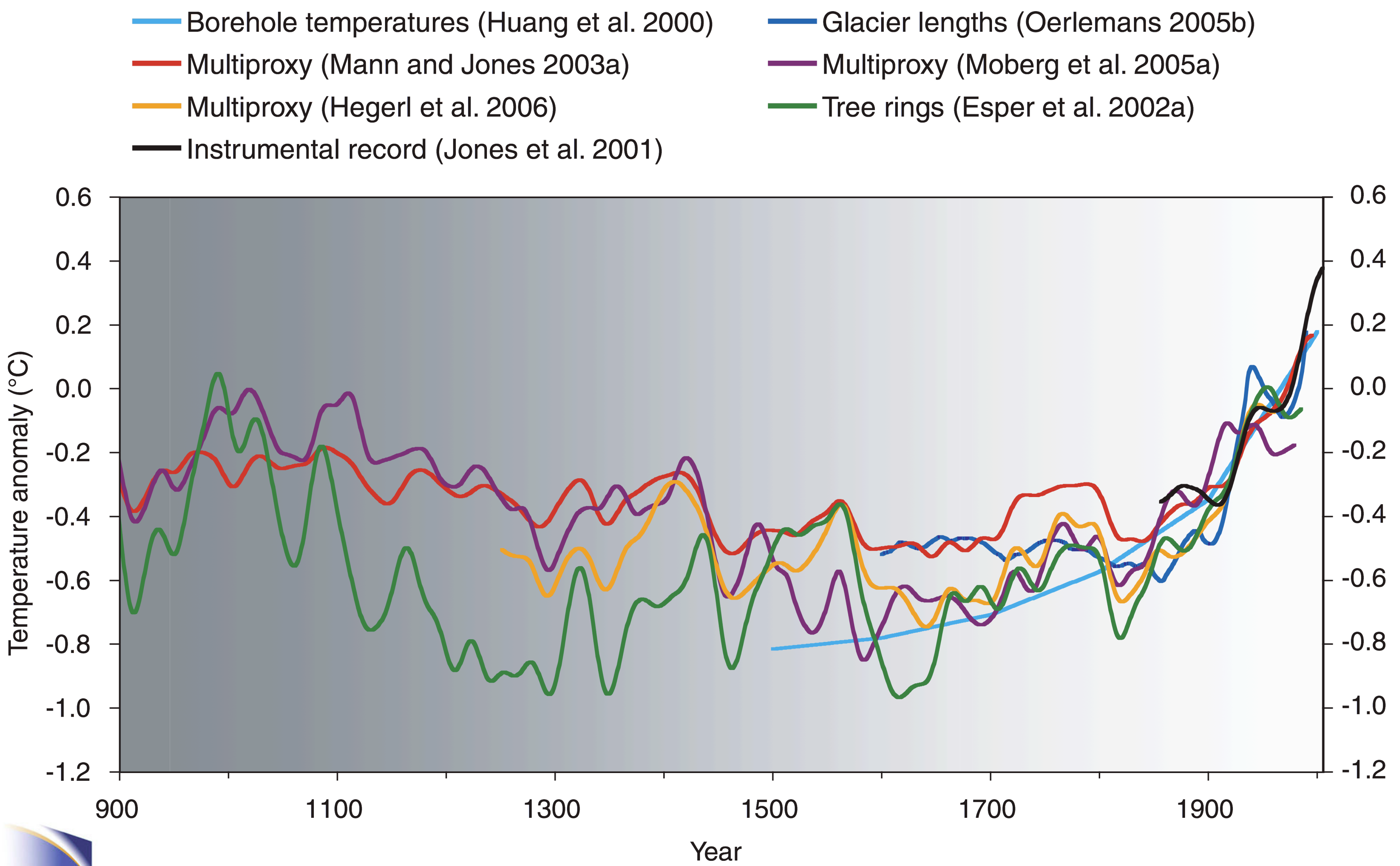
Temperature records and estimates



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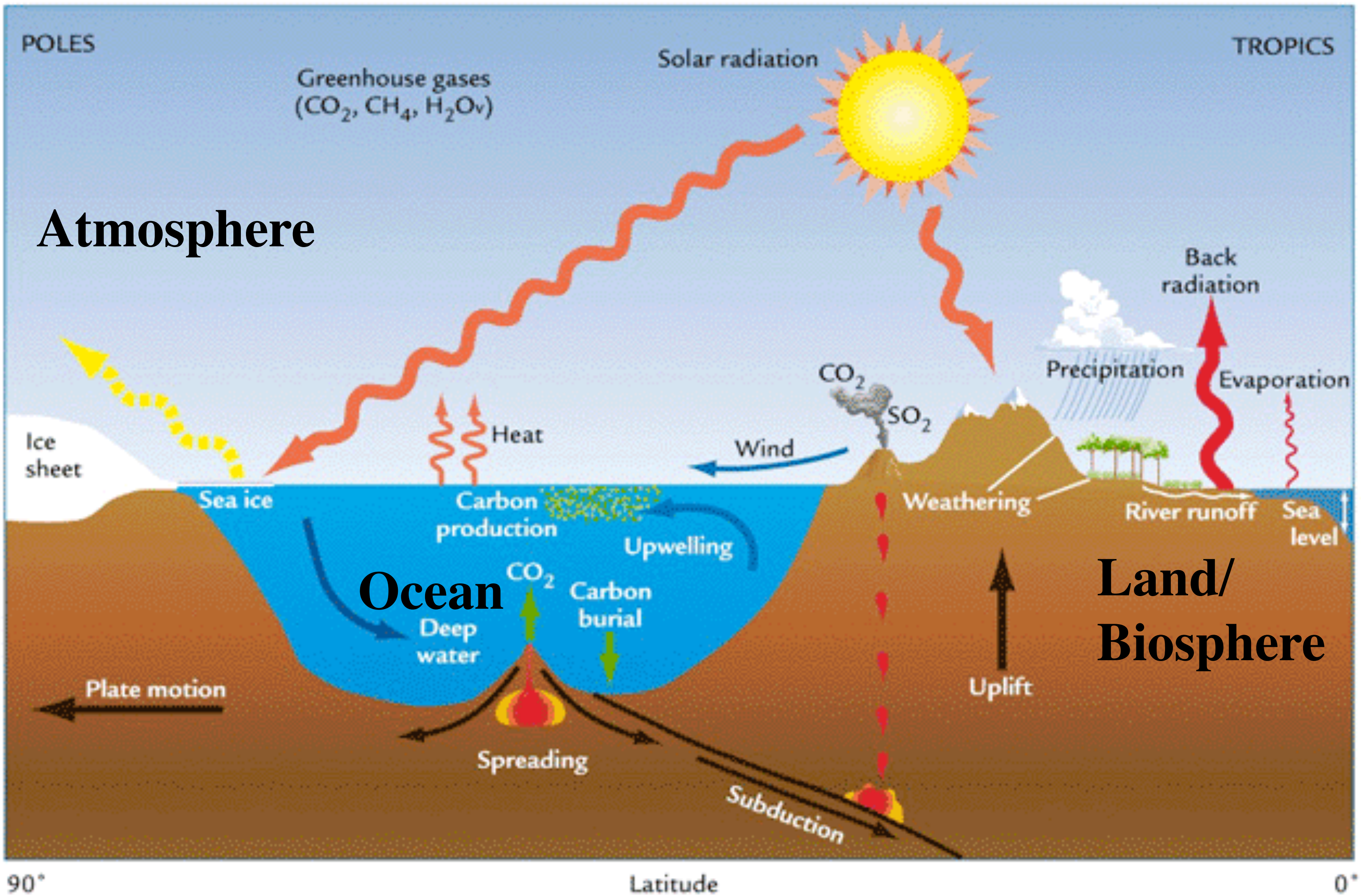
The Earth's climate system



Pole

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Equator

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

Atmospheric modeling hierarchy

Understanding has been aided by a hierarchy of approaches

Consider the flux form of thermodynamic energy equation

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

where T - temperature; $\mathbf{V}$ - horizontal wind vector; p - pressure; ω - vertical pressure velocity; Q_{rad} and Q_{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, $< S > - < F >= 0$

Atmospheric modeling hierarchy

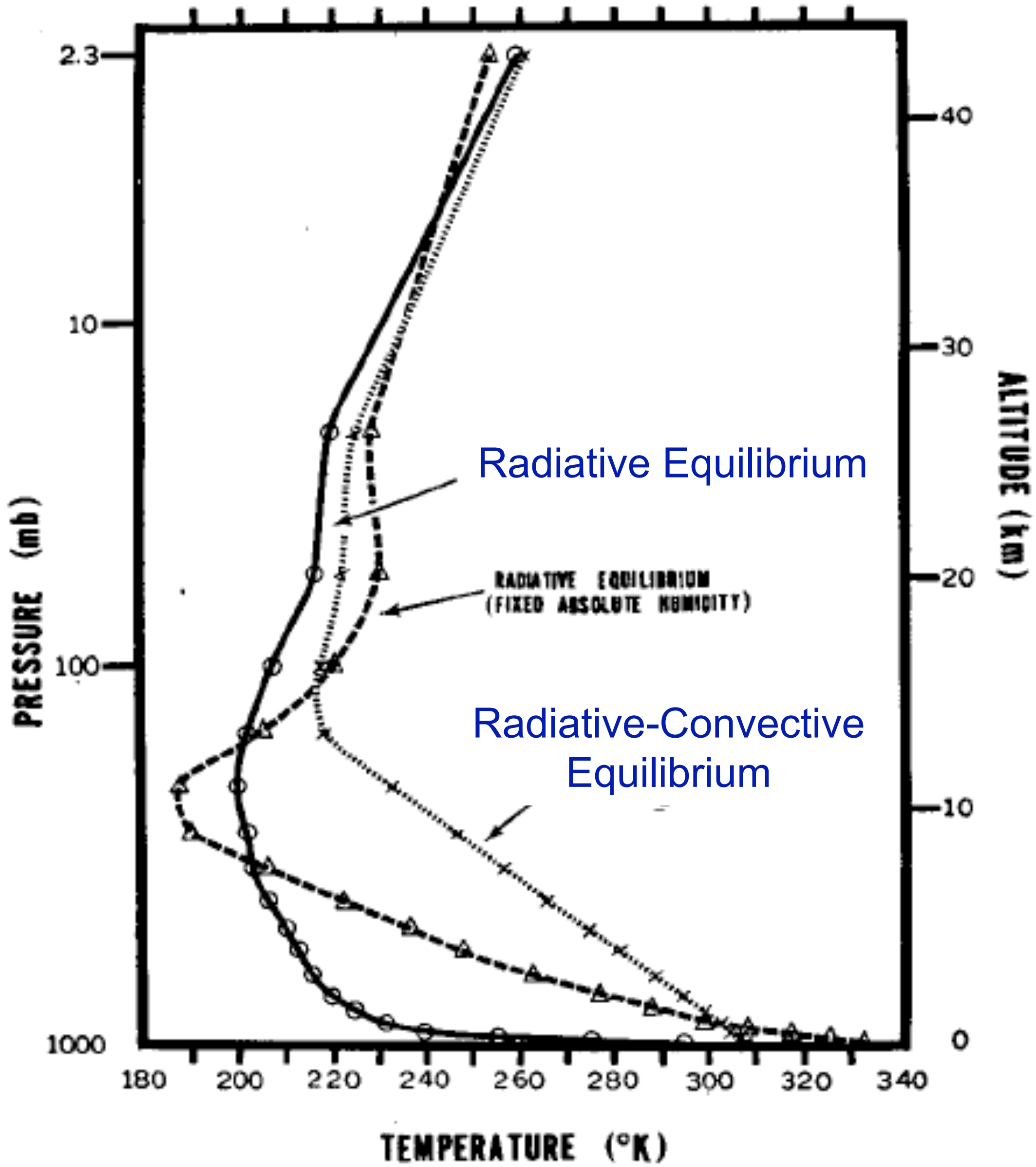
- Simple One-Dimensional (Radiative-Convective) Climate Model
  - Averaging (1) over horizontal space dimensions yields

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

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

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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

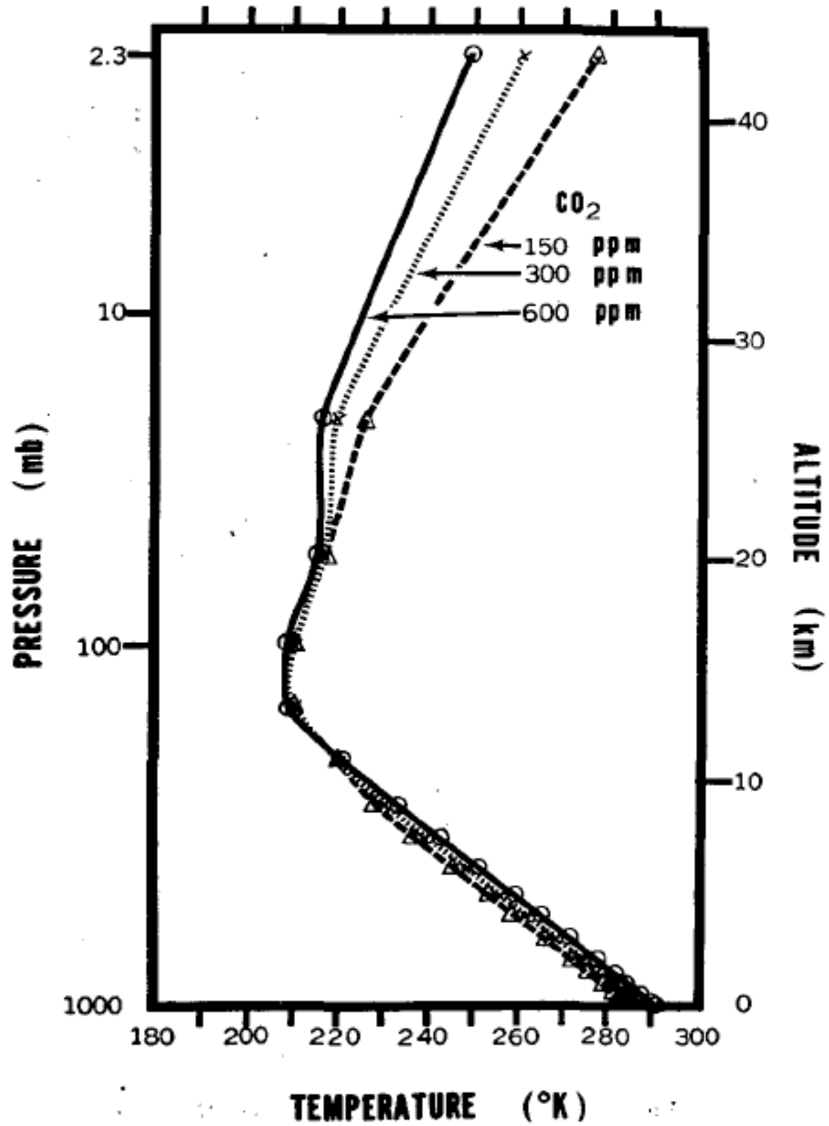
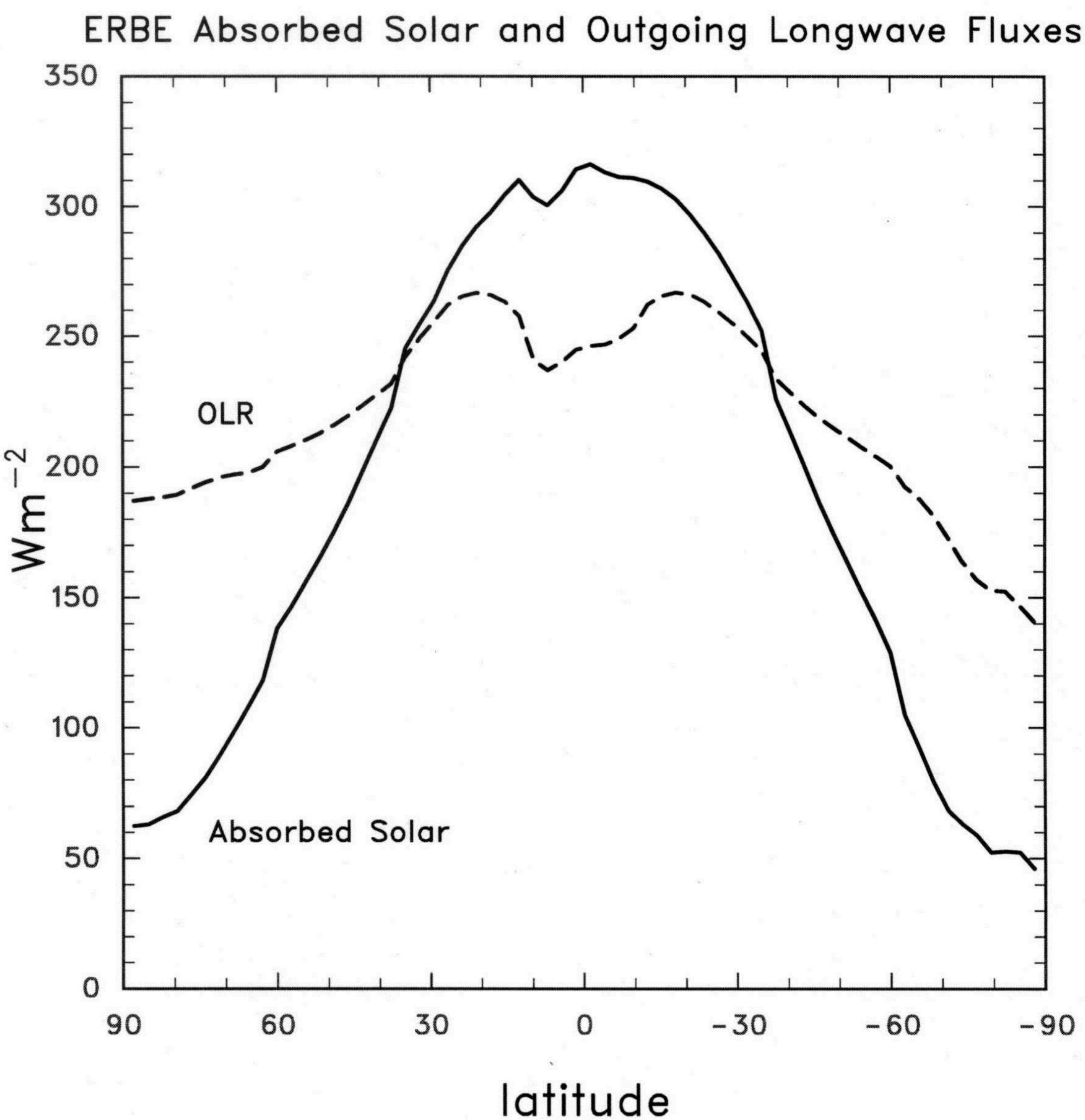


FIG. 16. Vertical distributions of temperature in radiative convective equilibrium for various values of CO_2 content.

Manabe & Wetherald 1967

Top of Atmosphere Radiation Component Fluxes



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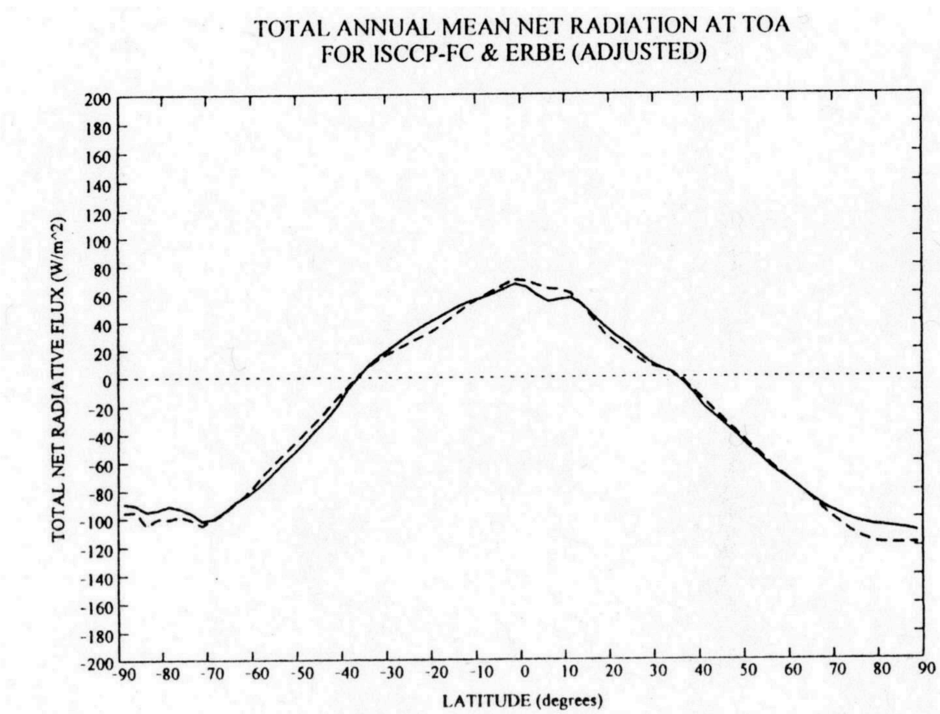
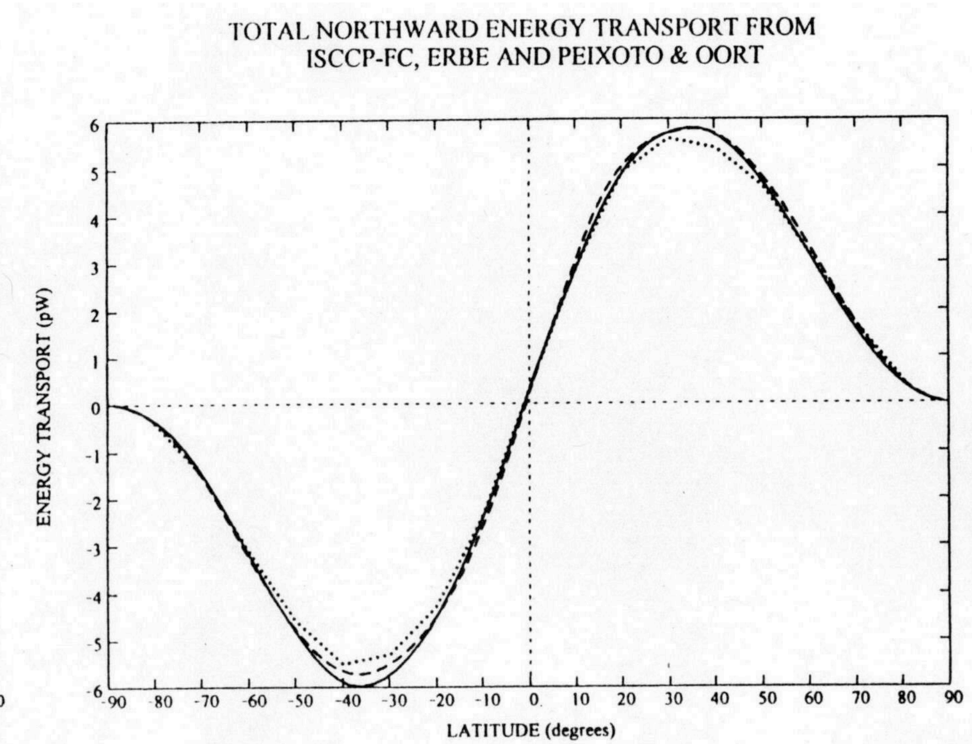
Top of Atmosphere Net Radiation Budget and Implied Meridional Energy Transport





Zhang and Rossow (1997)

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

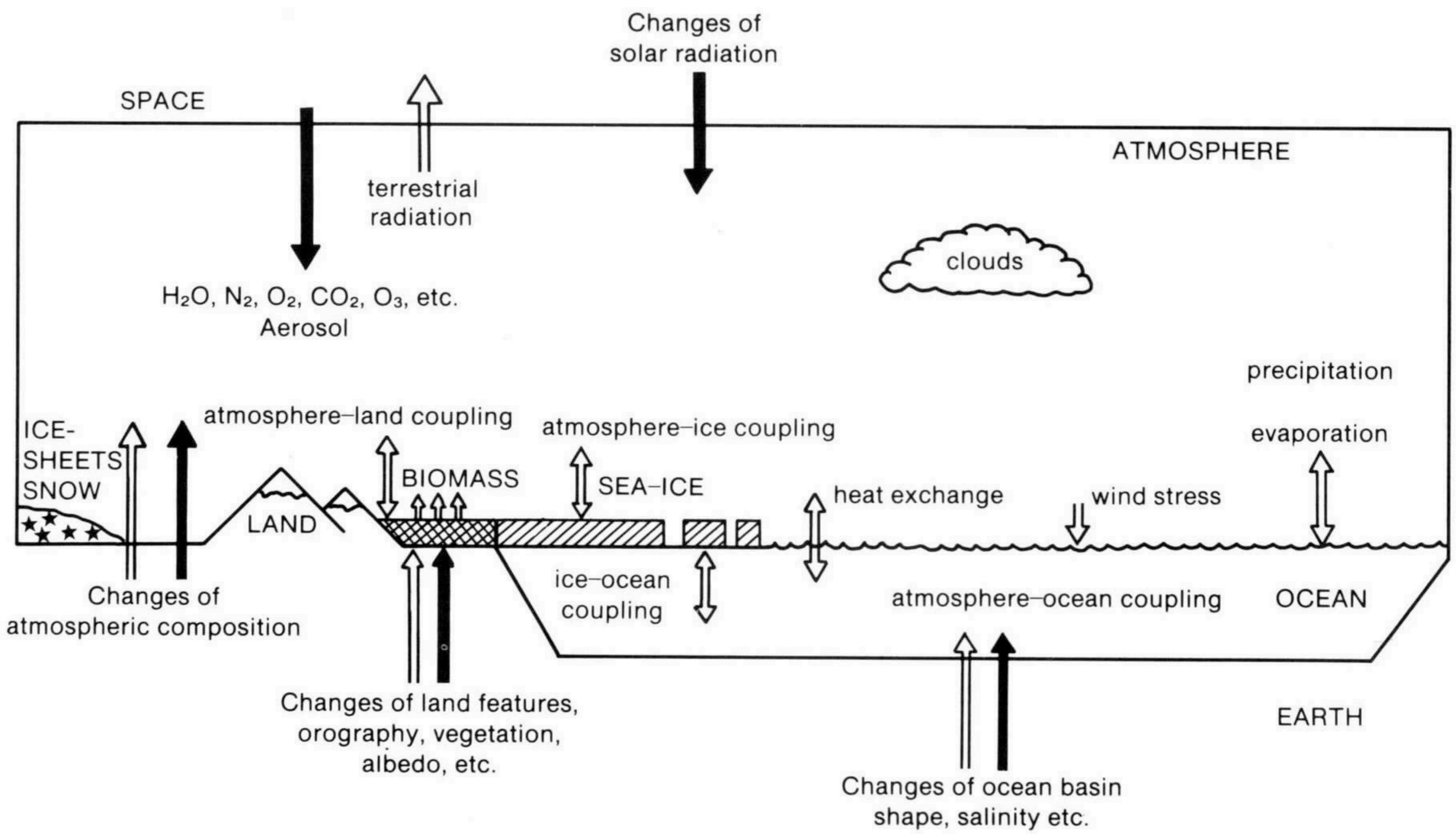


Figure 3.1: Schematic illustration of the components of the coupled atmosphere-ocean-ice-land climatic system. The full arrows are examples of external processes, and the open arrows are examples of internal processes in climatic change (from Houghton, 1984).

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

Meteorological Primitive Equations

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

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

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

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

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

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

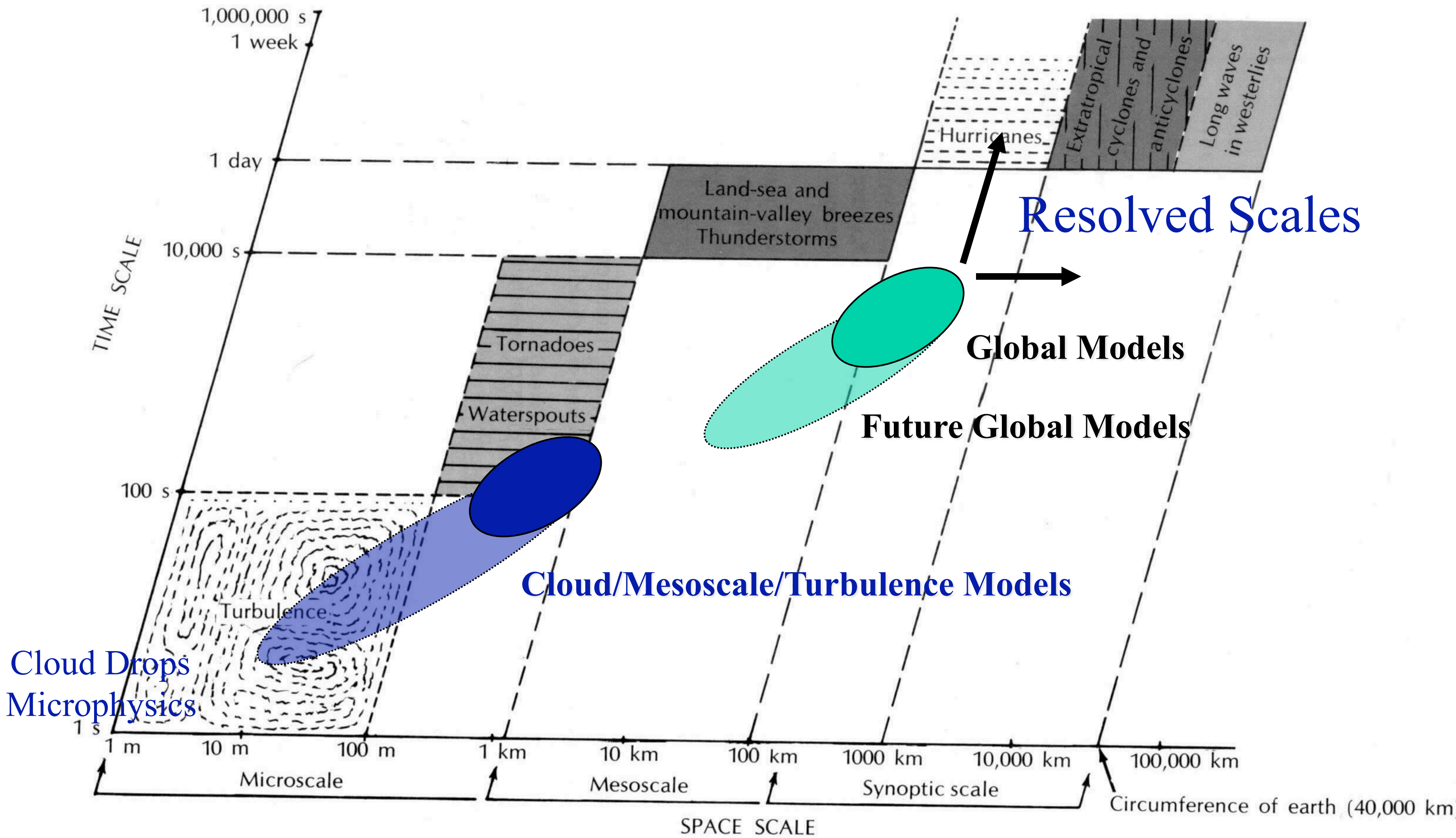
Harmless looking terms $\mathbf{F}$, Q, and $S_q \Longrightarrow$ "physics"

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)

Scales of Atmospheric Motions



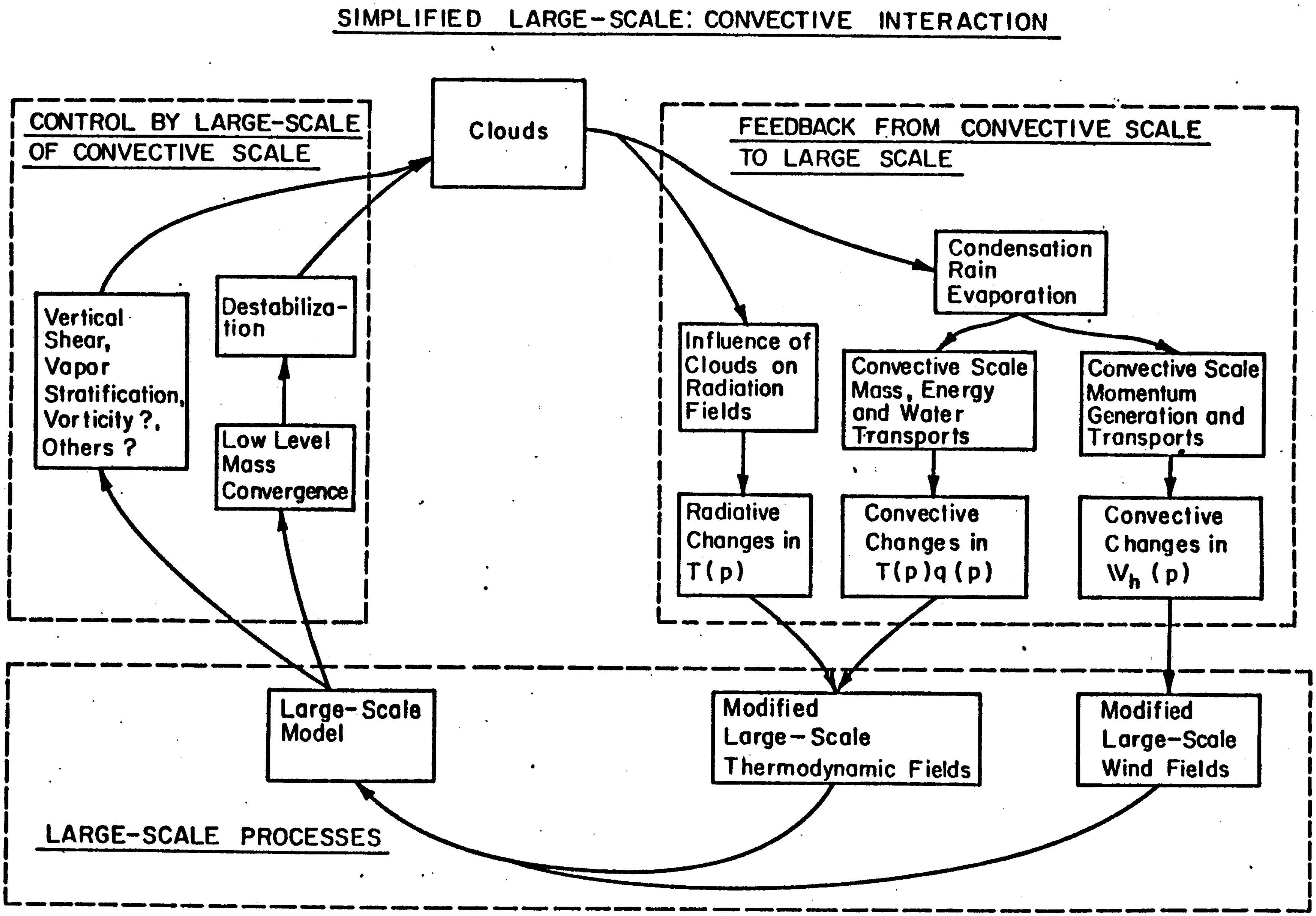
Anthes et al. (1975)

Parametrizations

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

Some important physical processes:

- 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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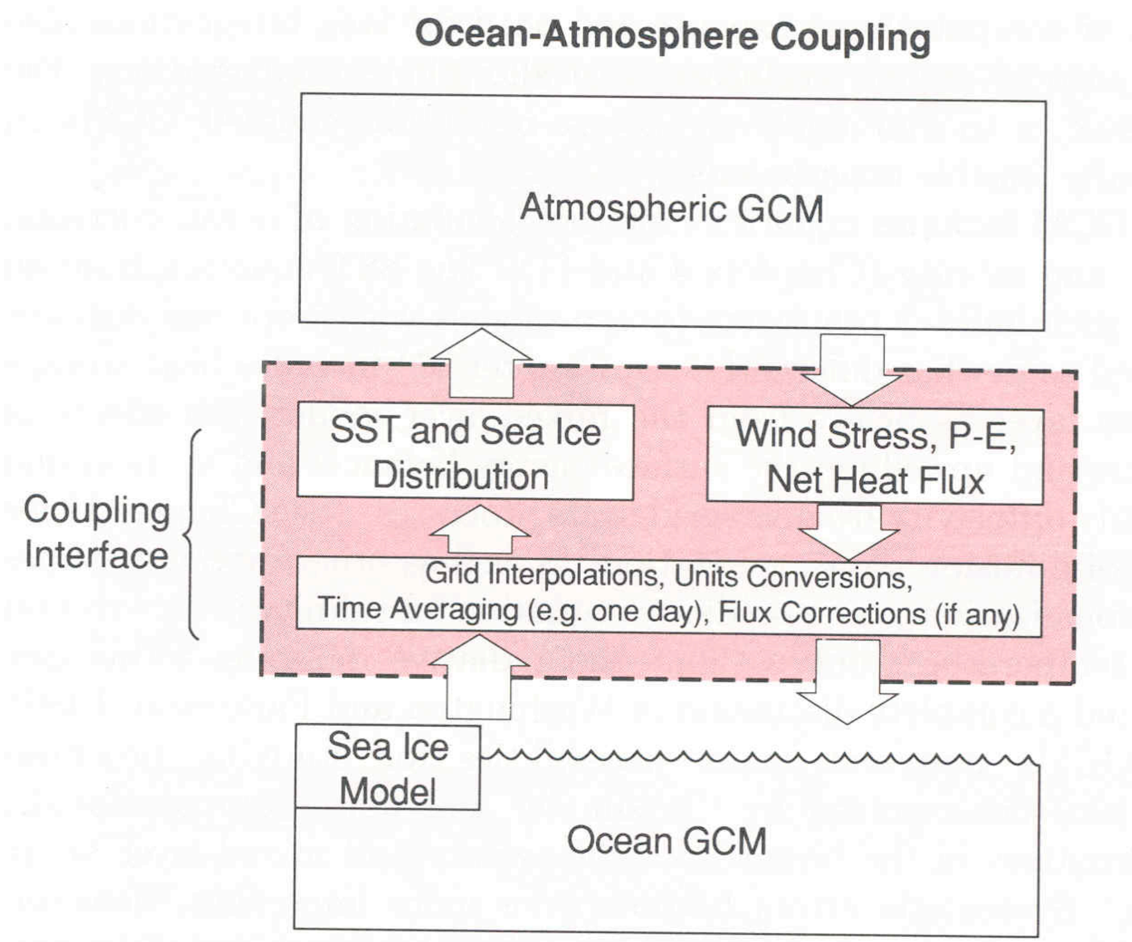
Coupled Models = Increased Technical Complexity



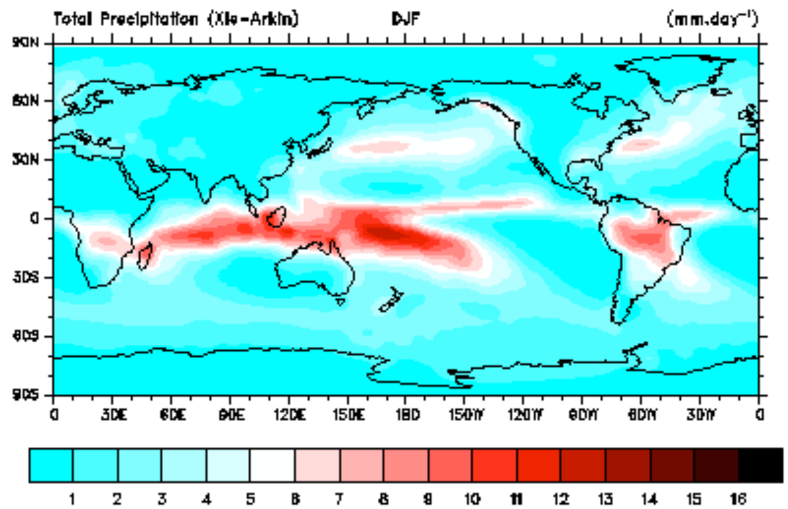
Note: Ocean GCM's are as complex as Atmosphere GCM's!

How can we evaluate simulation quality?

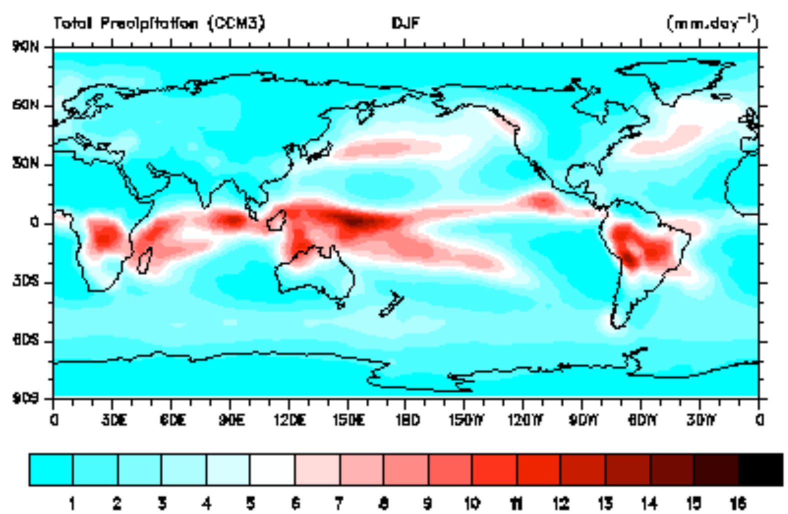
- Continue to compare long term mean climatology
  - average mass, energy, and momentum balances
  - tells you where the physical approximations take you
    - ***but you don't necessarily know how you get there!***
- Must also consider dominant modes of variability
  - provides the opportunity to evaluate *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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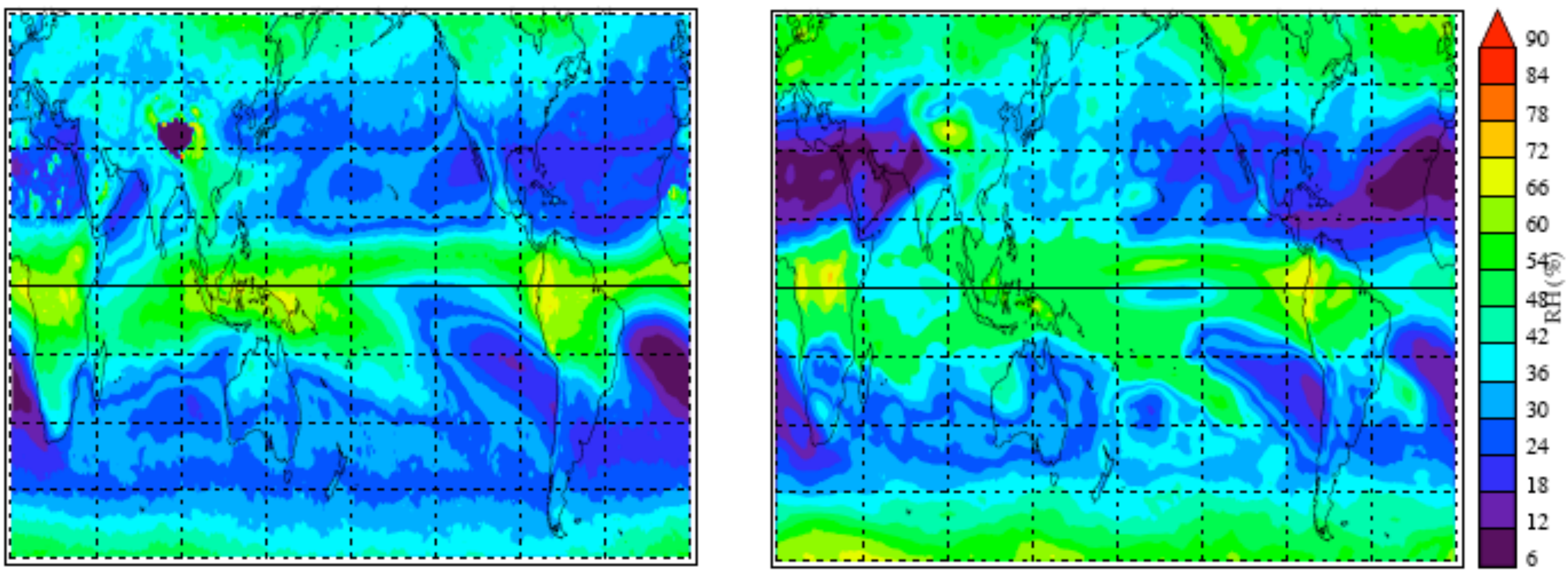
Mean Biases

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

Observed

Simulated



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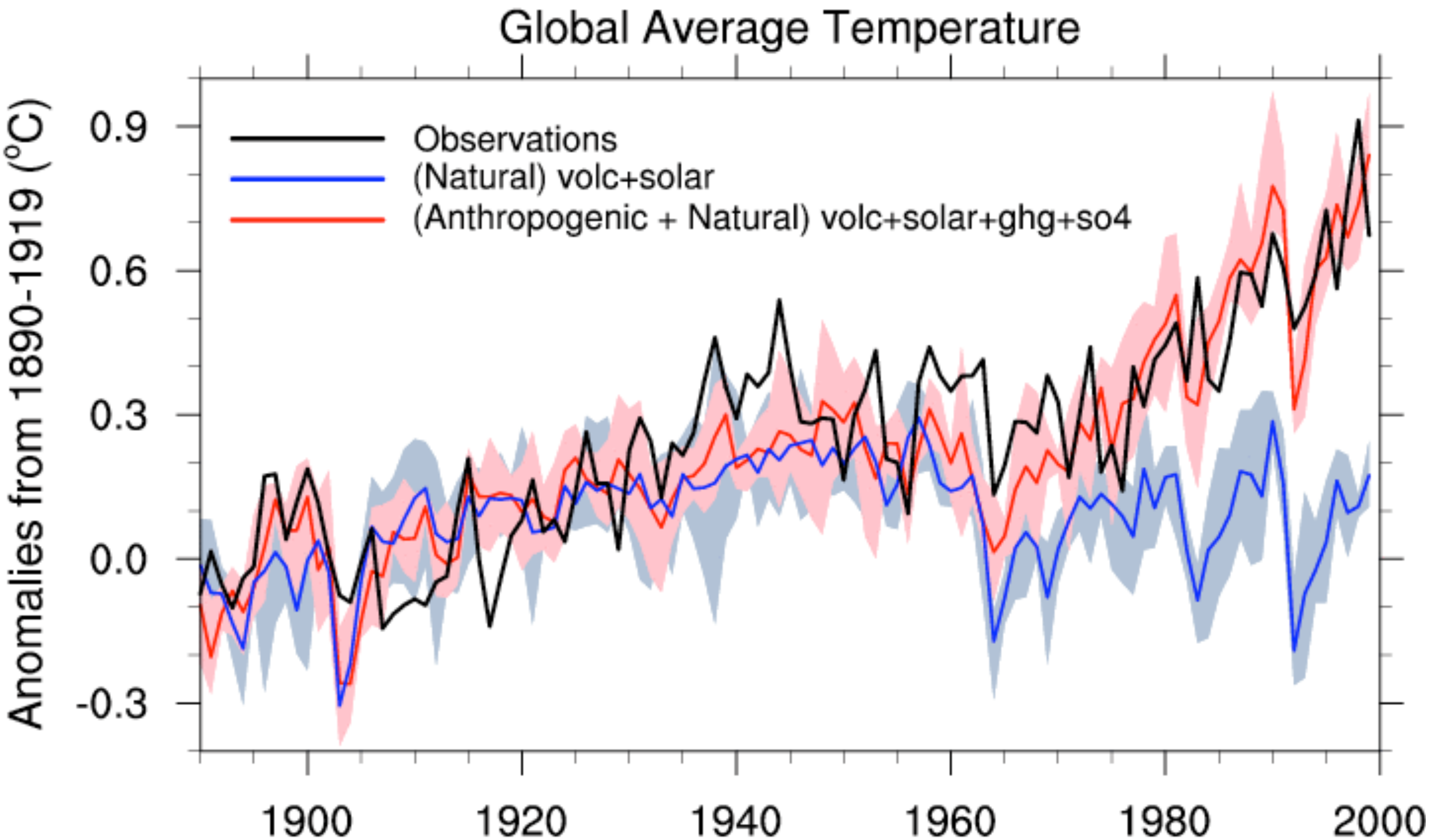
Observations: 20th Century Warming

Model Solutions with Human Forcing



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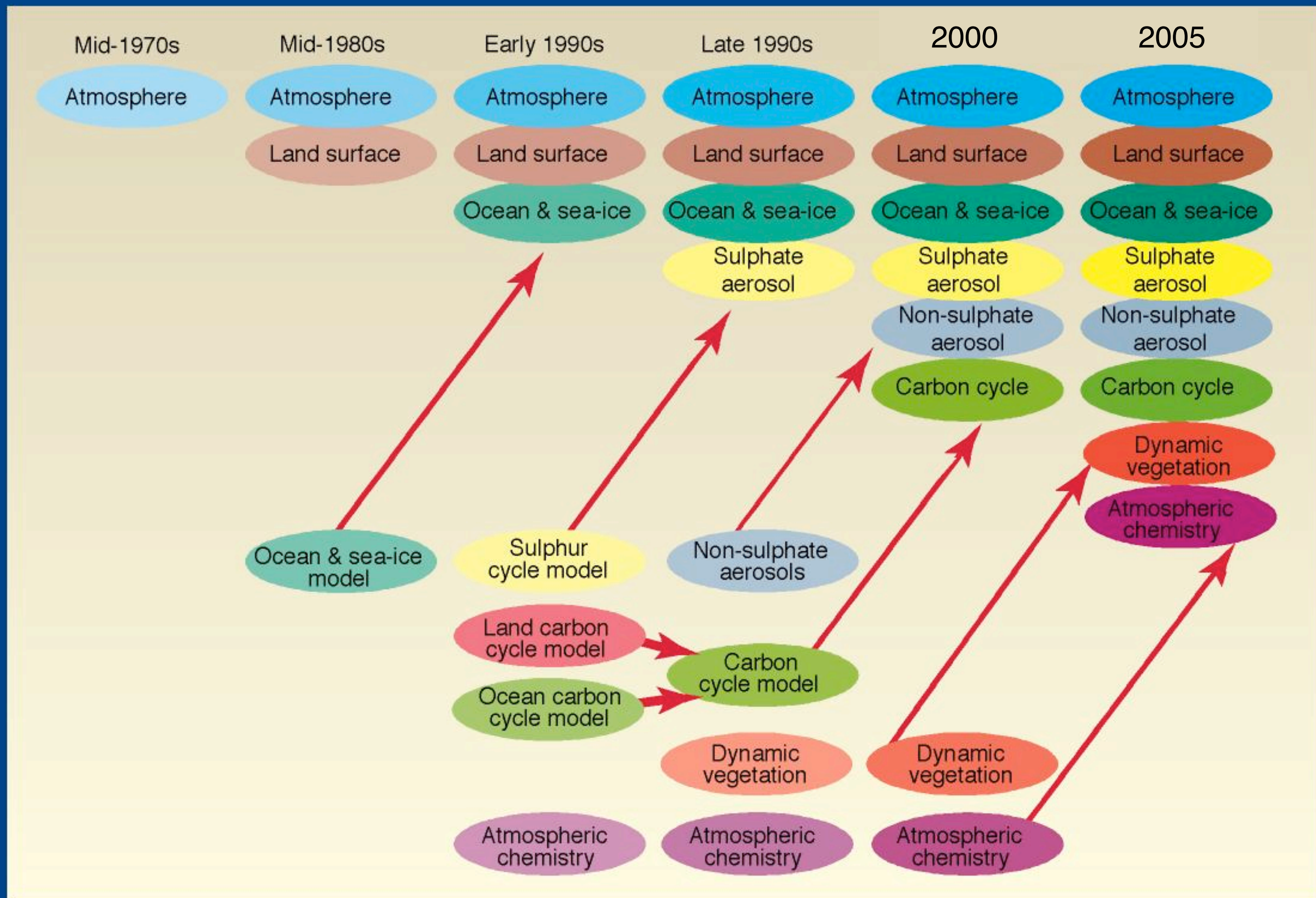
Climate Model 'Evolution'

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