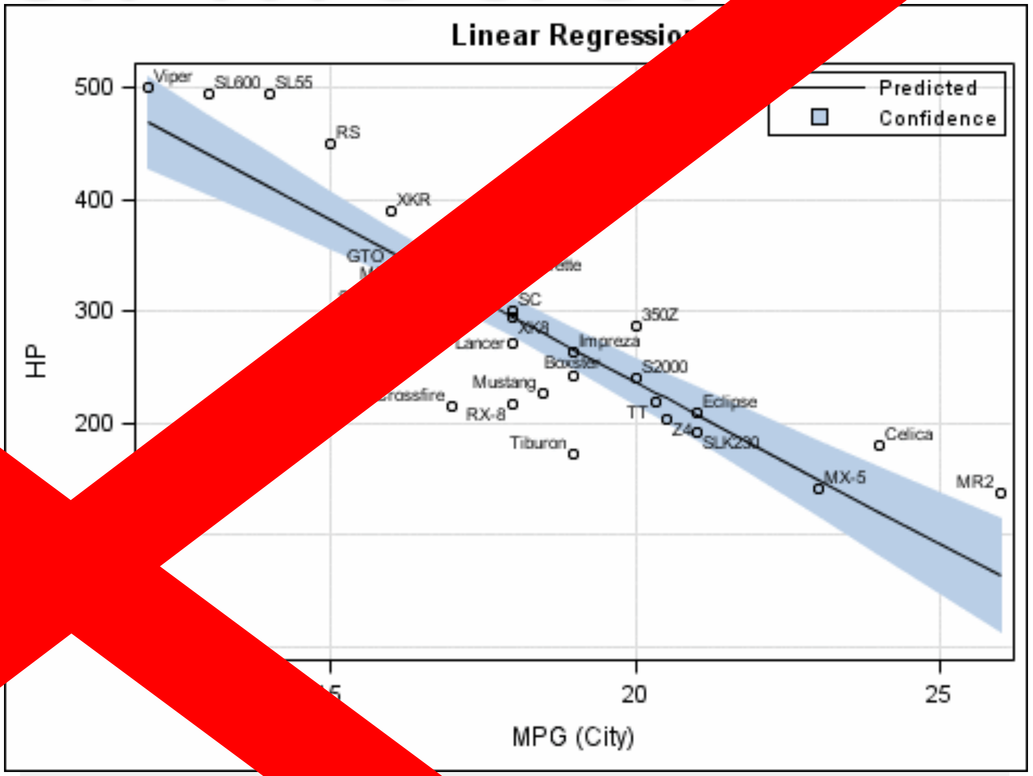
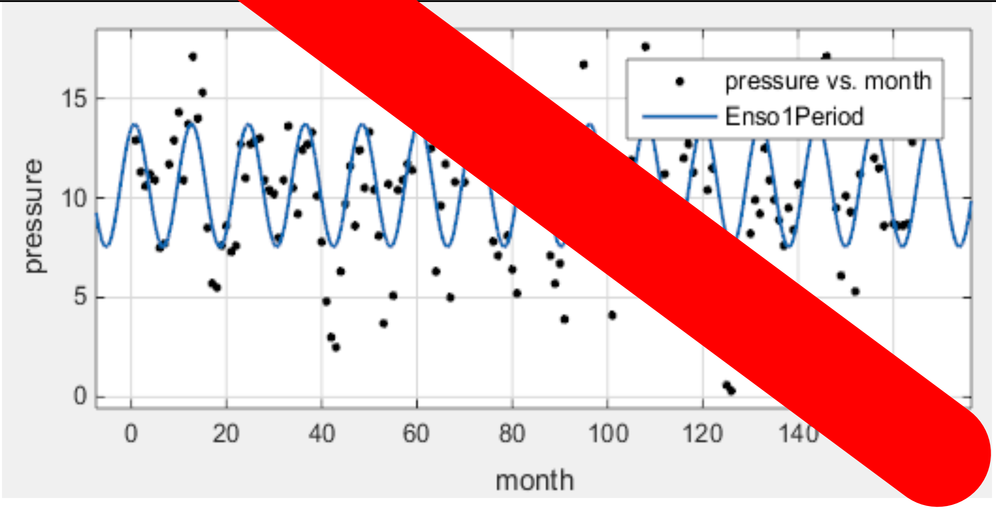
# Earth System Models

## Module 7

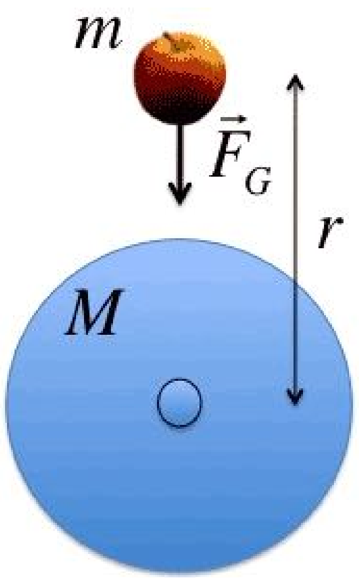
# Empirical Models

- Generalized mathematical formulation with adjustable coefficients
- Combinations of
  - polynomials
  - exponential growth & decay
  - Periodic sines and cosines
- Coefficients fit to data (e.g., least squares)



# Deterministic Models

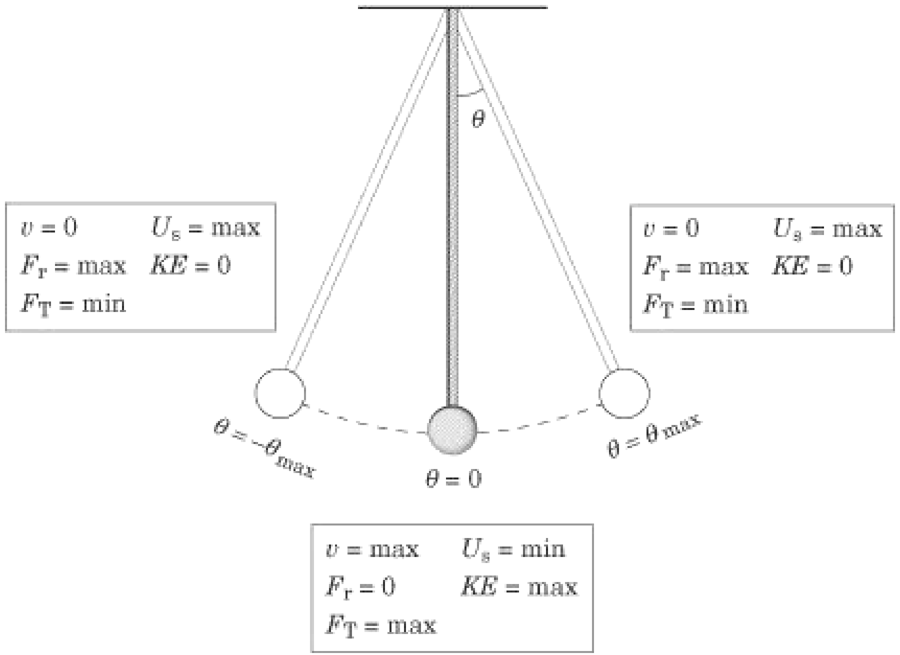



$$F = ma$$

$$\frac{GMm}{r^2} = ma$$

Then, cancelling $m$ on both sides:

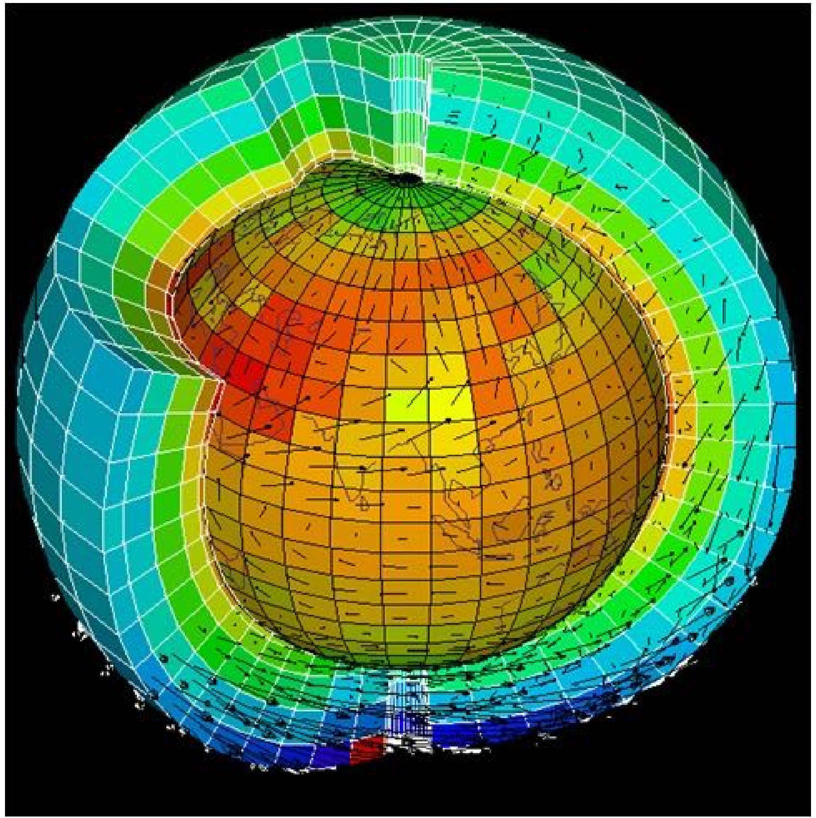
$$a = \frac{GM}{r^2} = g$$



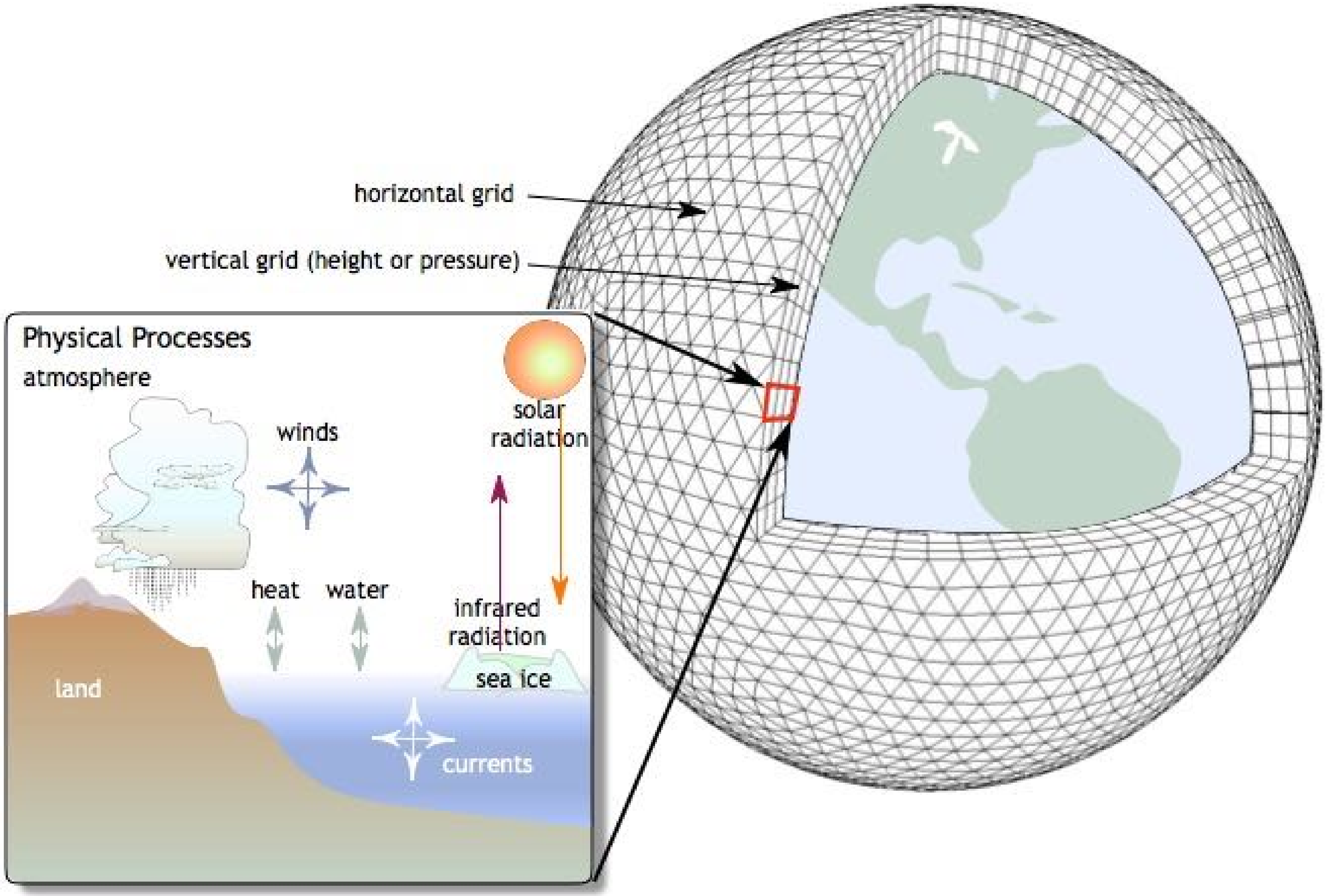

- Formulated as "cause and effect"
- Common in physics and chemistry
- Usually take the form of differential equations
- Initial & boundary-value problems
- May still have adjustable coefficients

- Deterministic, not empirical
- "F = ma of a compressible fluid on a rotating sphere with radiation, thermodynamics, and phase transitions"
- Allow detailed prediction of future states at high resolution in both space and time
- Same equations:
  - Weather forecasting (initial value problem)
  - Climate simulation (boundary value problem)

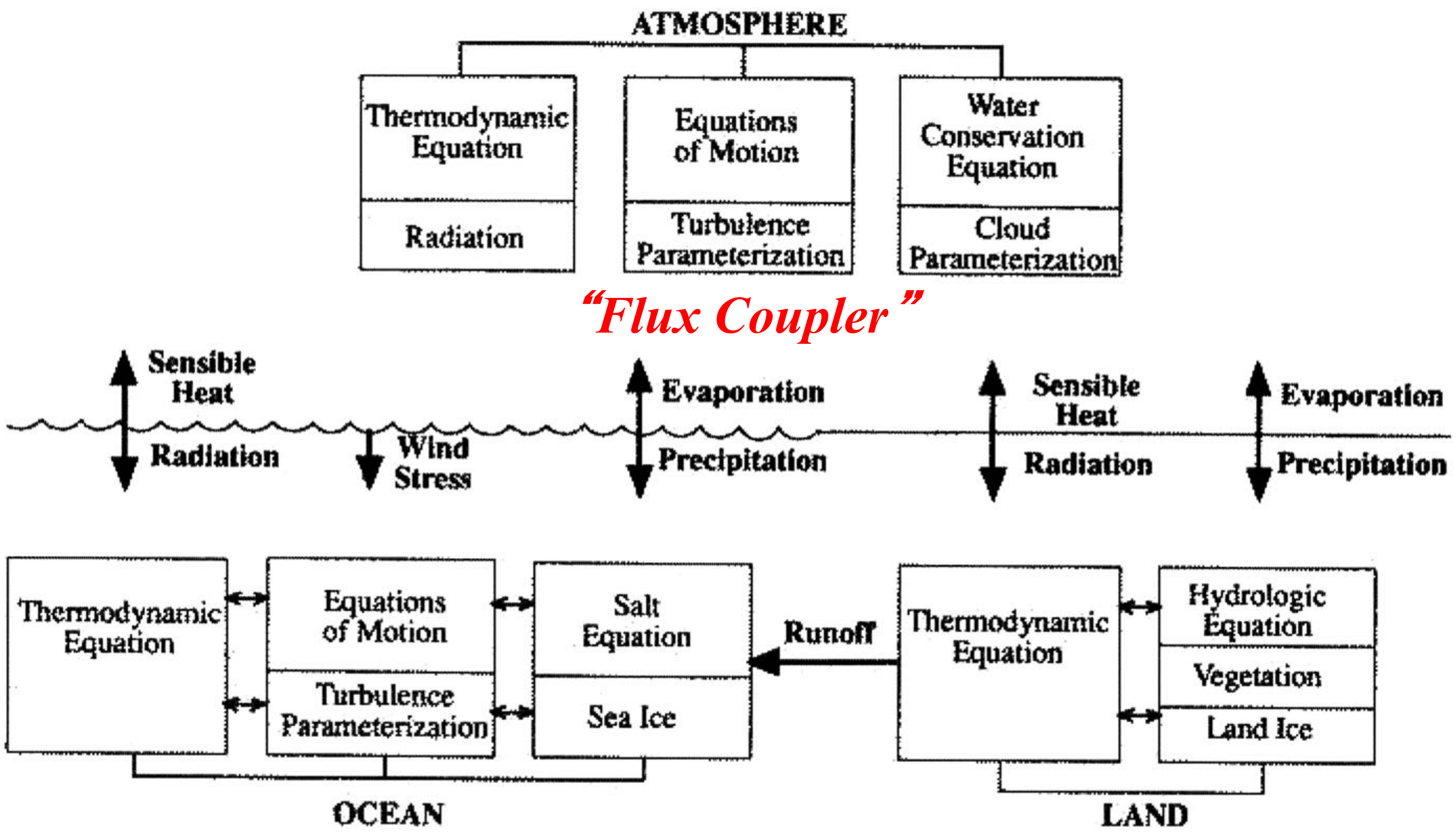
# "General Circulation Models" (GCMs)



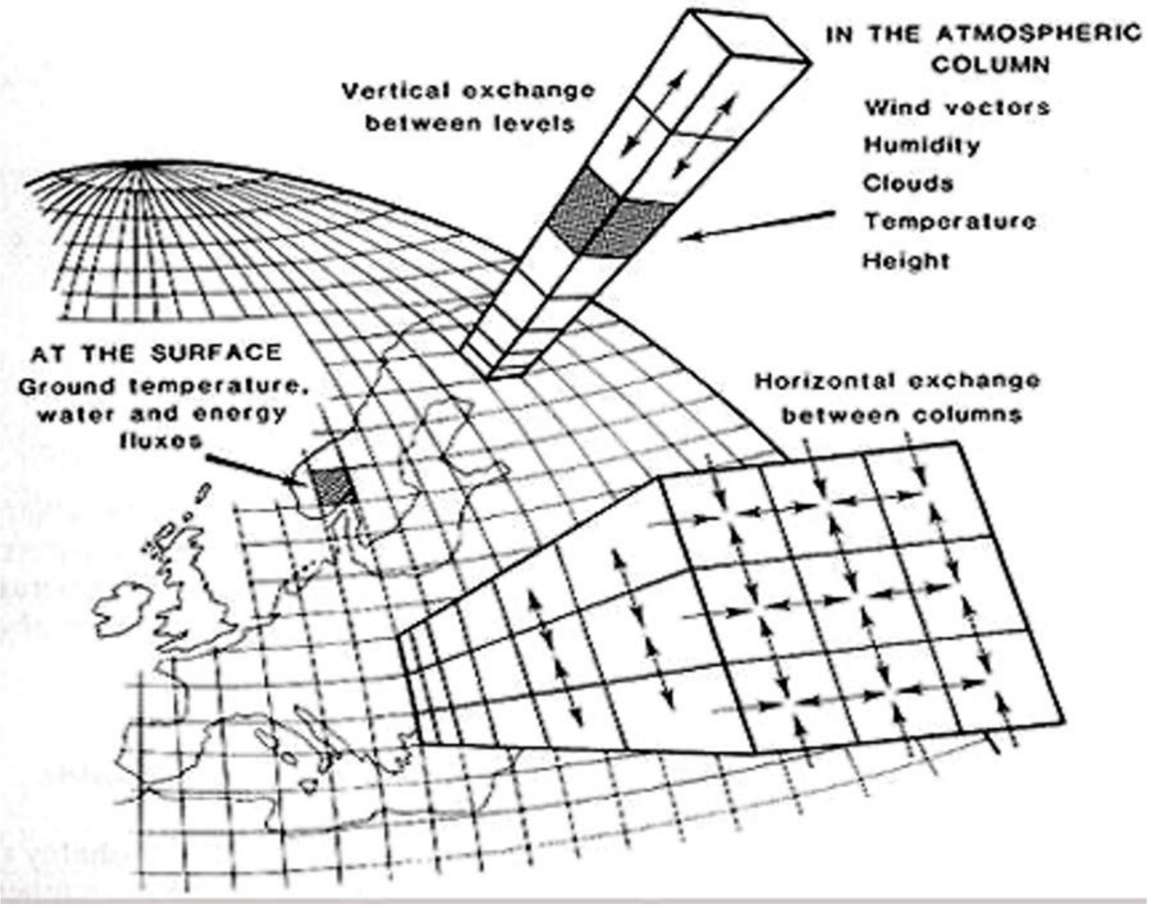
# Climate Model Processes



# Climate Model Structure

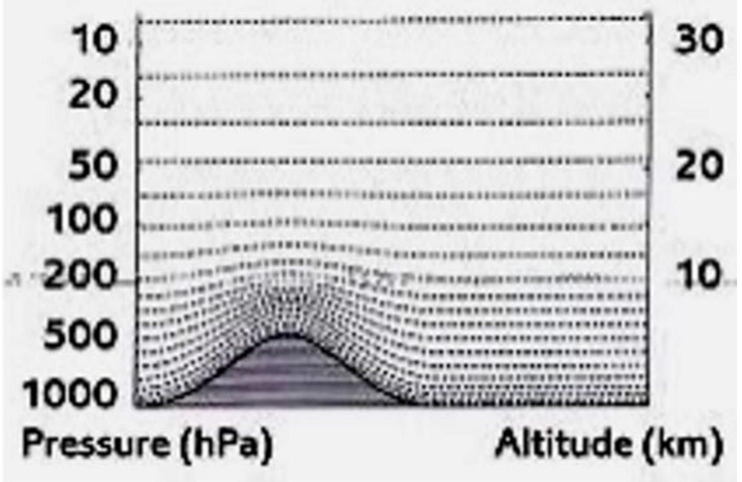


# Climate Model Grids

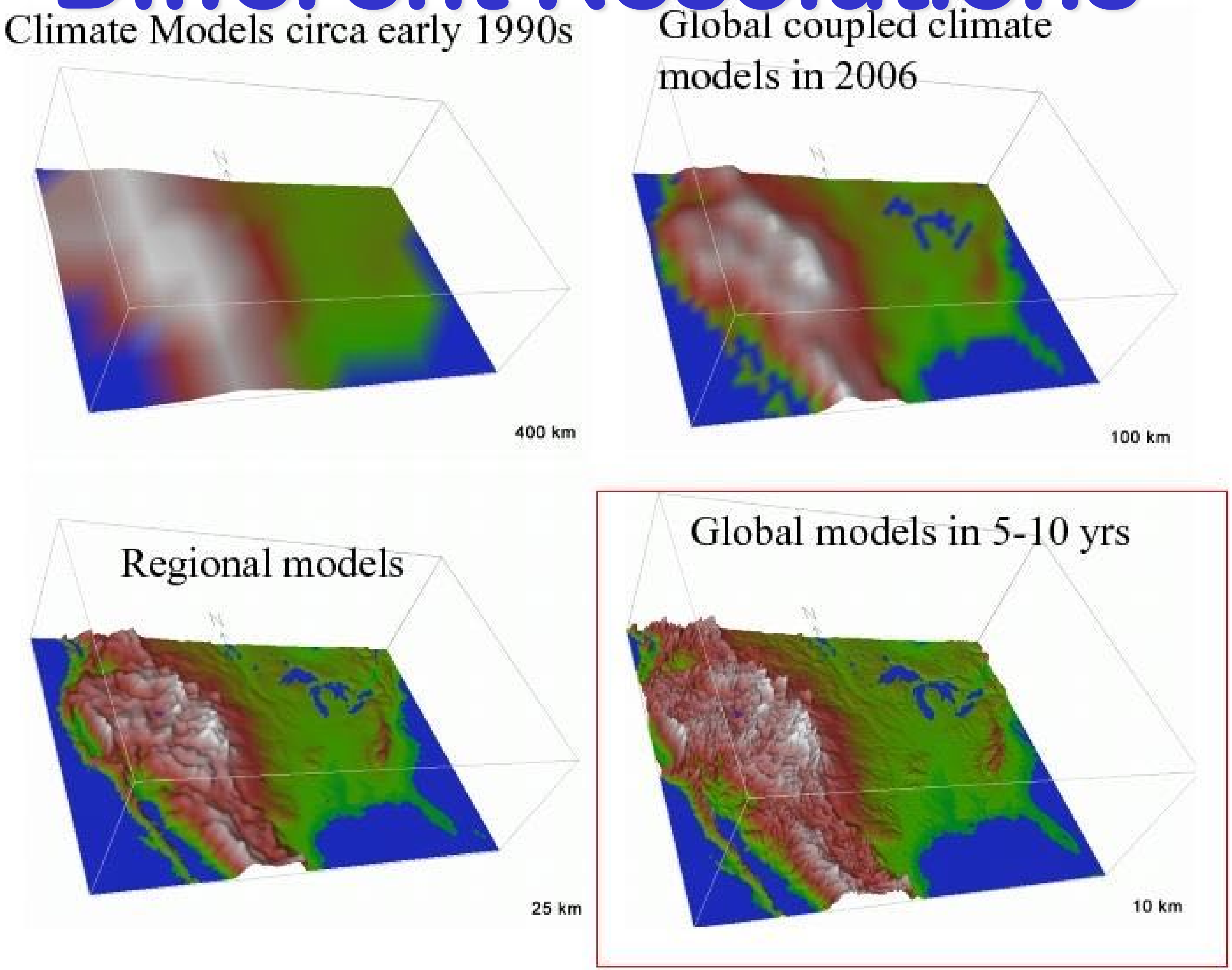



**Typical climate model**
**$\Delta x \sim 100$ km**

**Typical weather forecast model**
**$\Delta x \sim 12$ km**

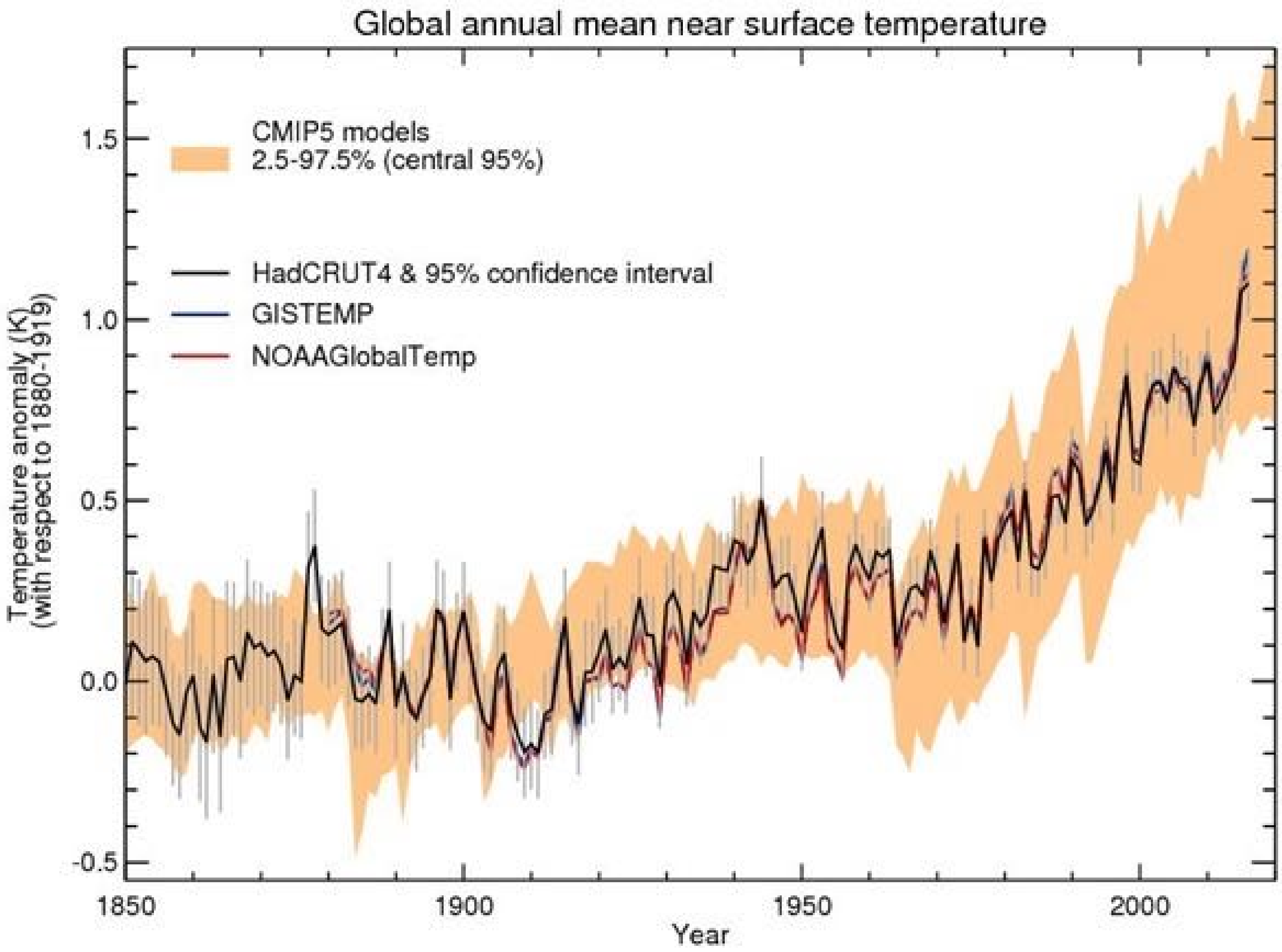


# Topography at Different Resolutions

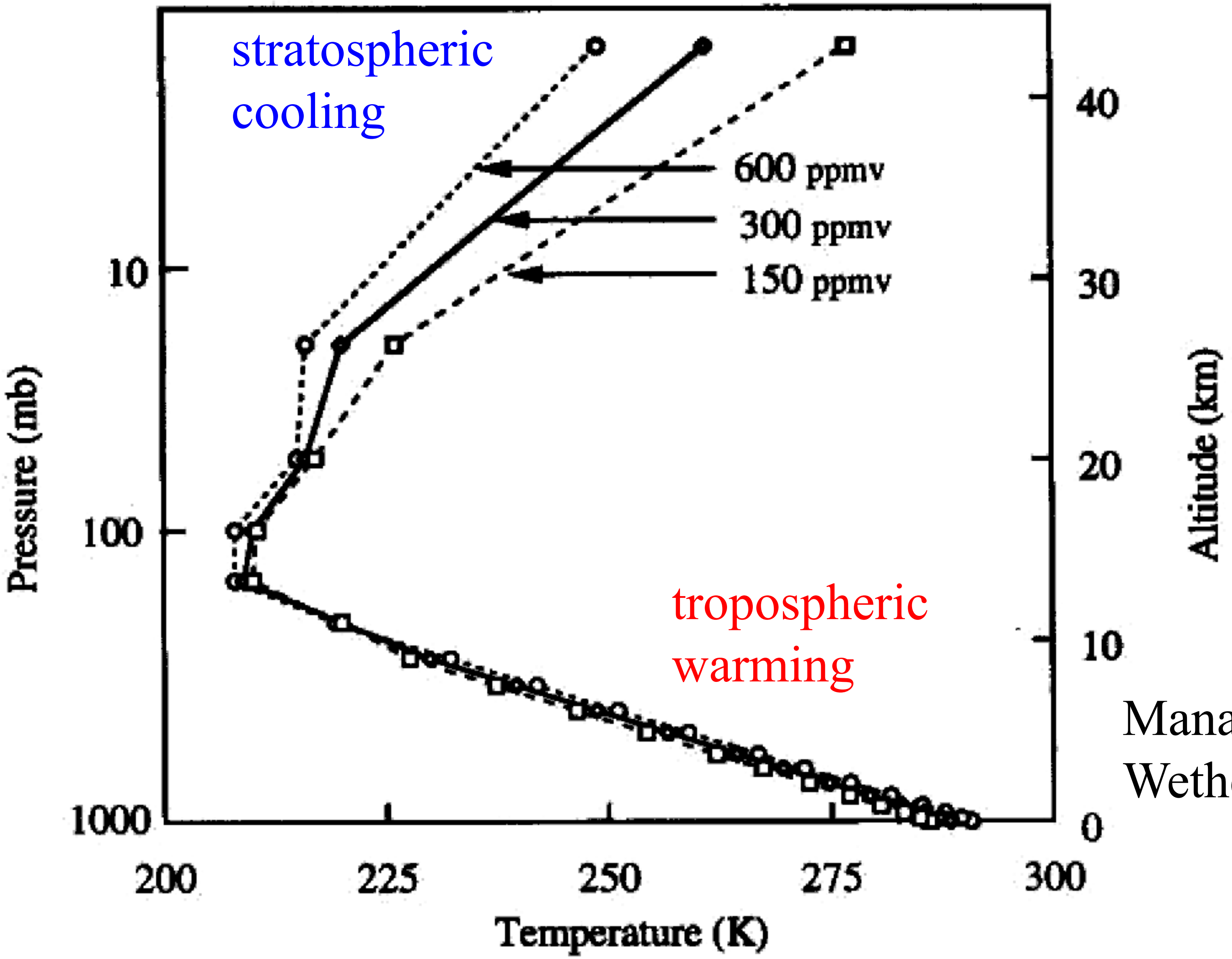



Optimistic view on model-developement

# Climate Model "Hindcasts"



# Warming under Cooling




Manabe and Wetherald (1967)

# Predicted Vertical Structure

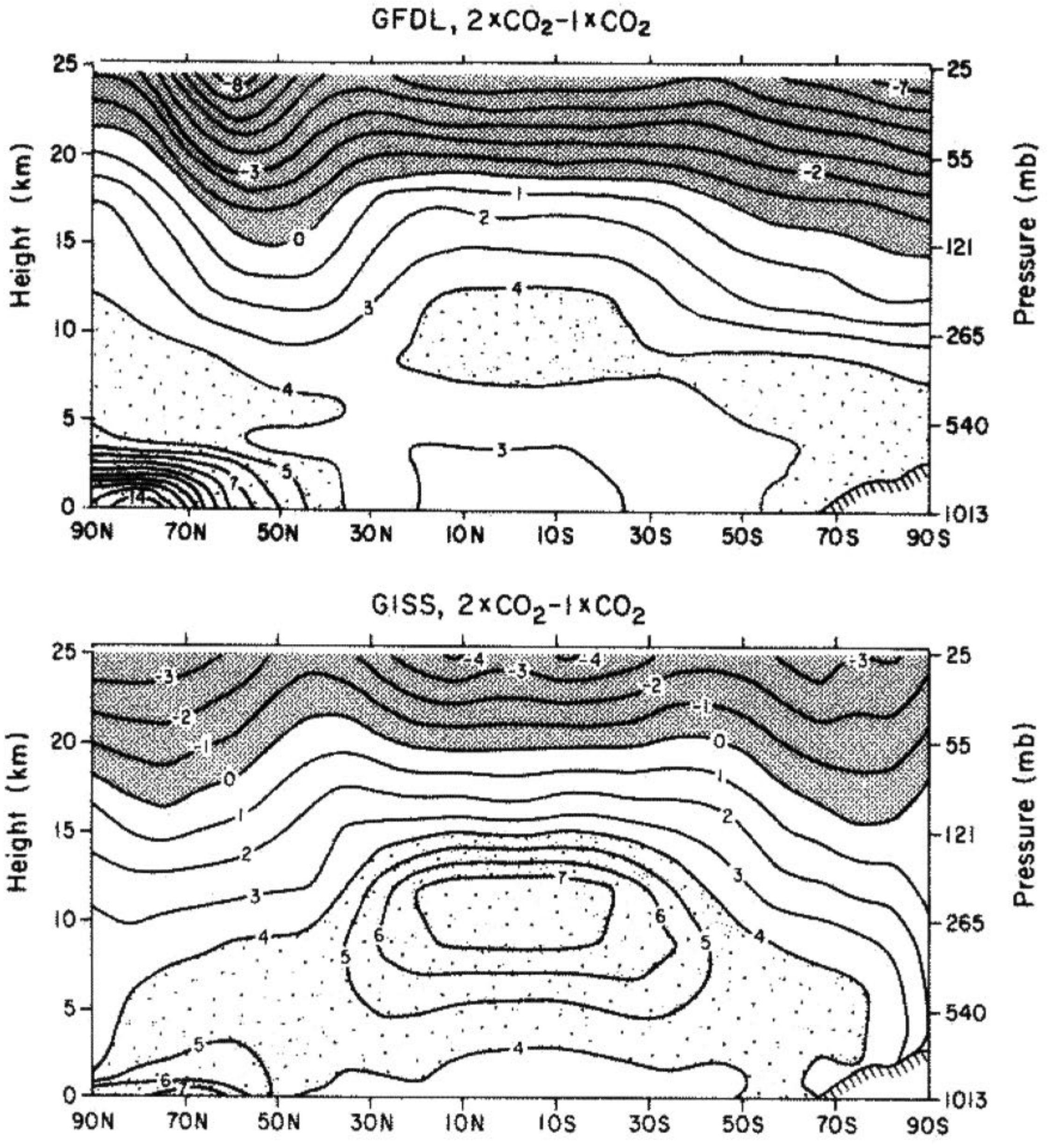
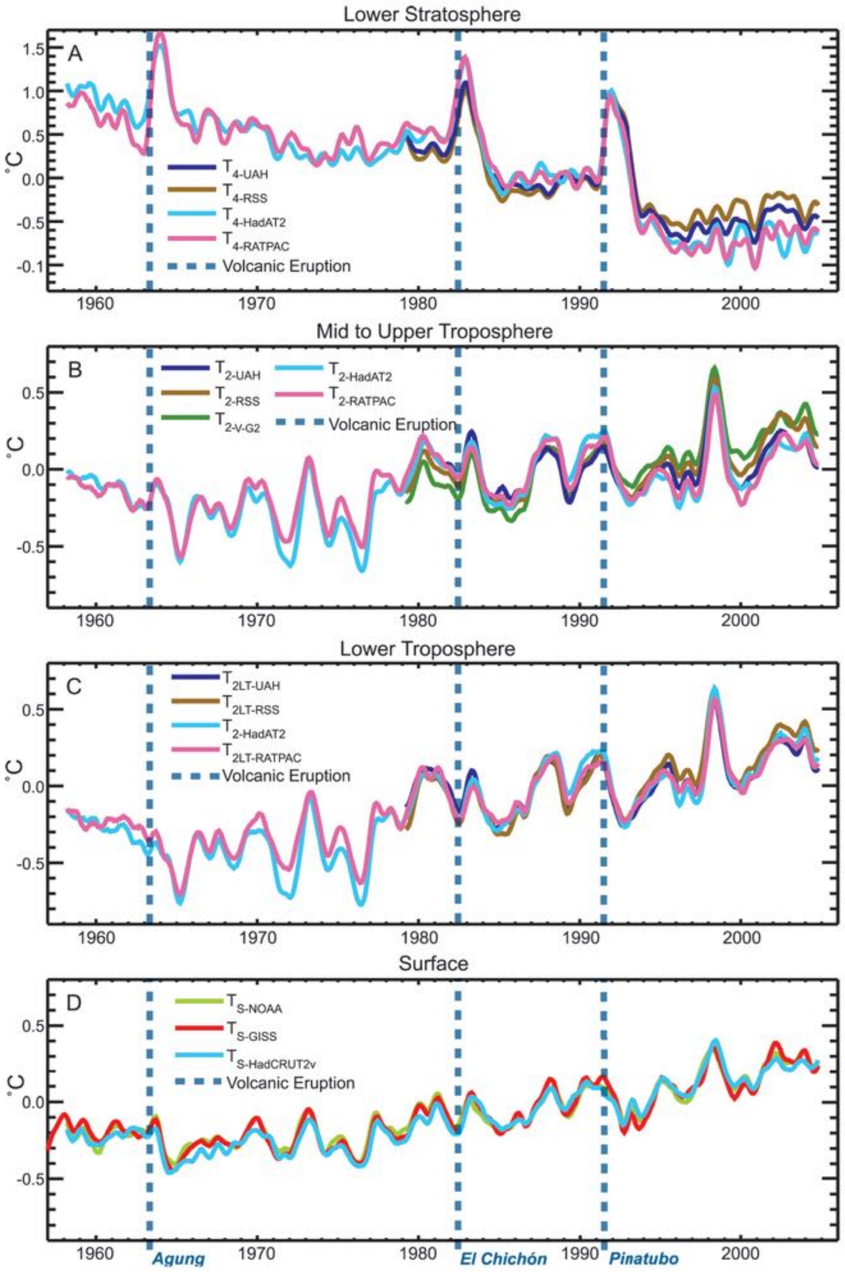


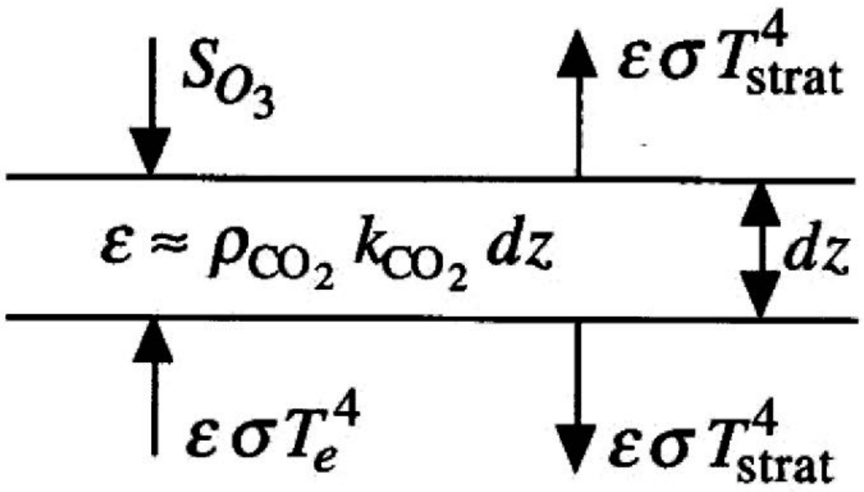

**Fig. 12.9** Contour plot of the zonally averaged change in air temperature during DJF resulting from a $CO_2$ doubling in two models that each give a global-average surface temperature increase of 4°C. Cooling and warming greater than 4°C are shaded. [Top panel, Wetherald and Manabe (1986), reprinted with permission from Kluwer Academic Publishers; bottom panel, Hansen *et al.* (1984), © American Geophysical Union, as printed in Schlesinger and Mitchell (1987), © American Geophysical Union.]

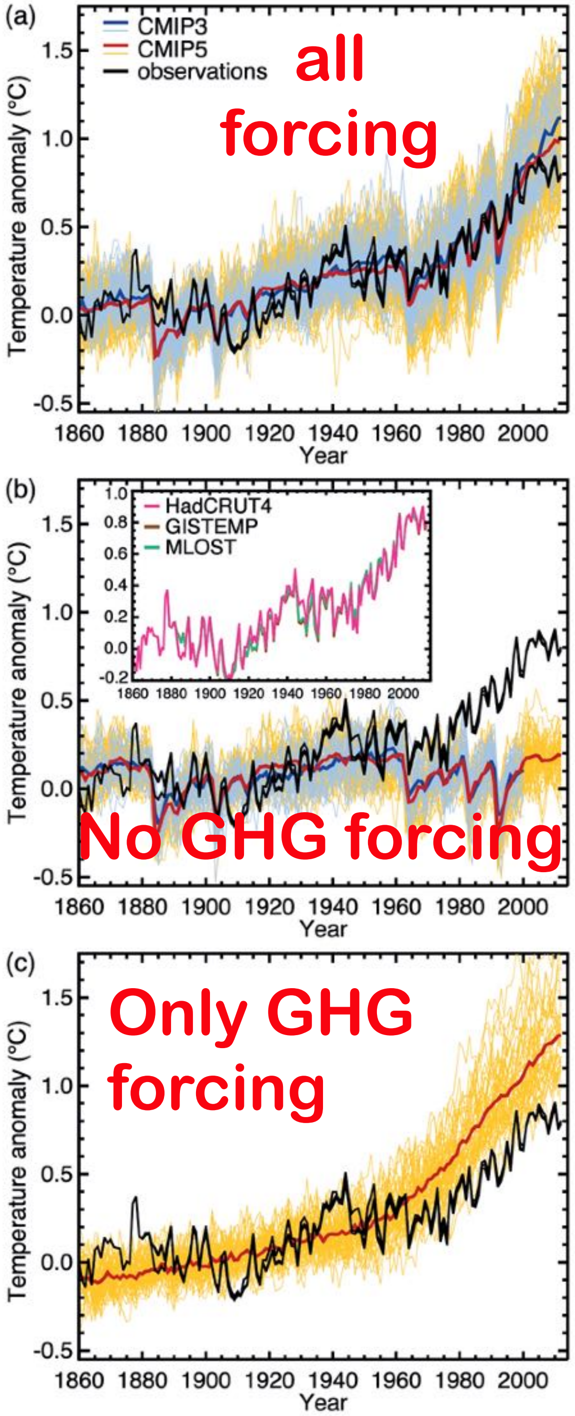
- Greenhouse "signature" is tropospheric warming and stratospheric cooling
- Predicted in mid-1980's by climate models

Observed Air Temperatures



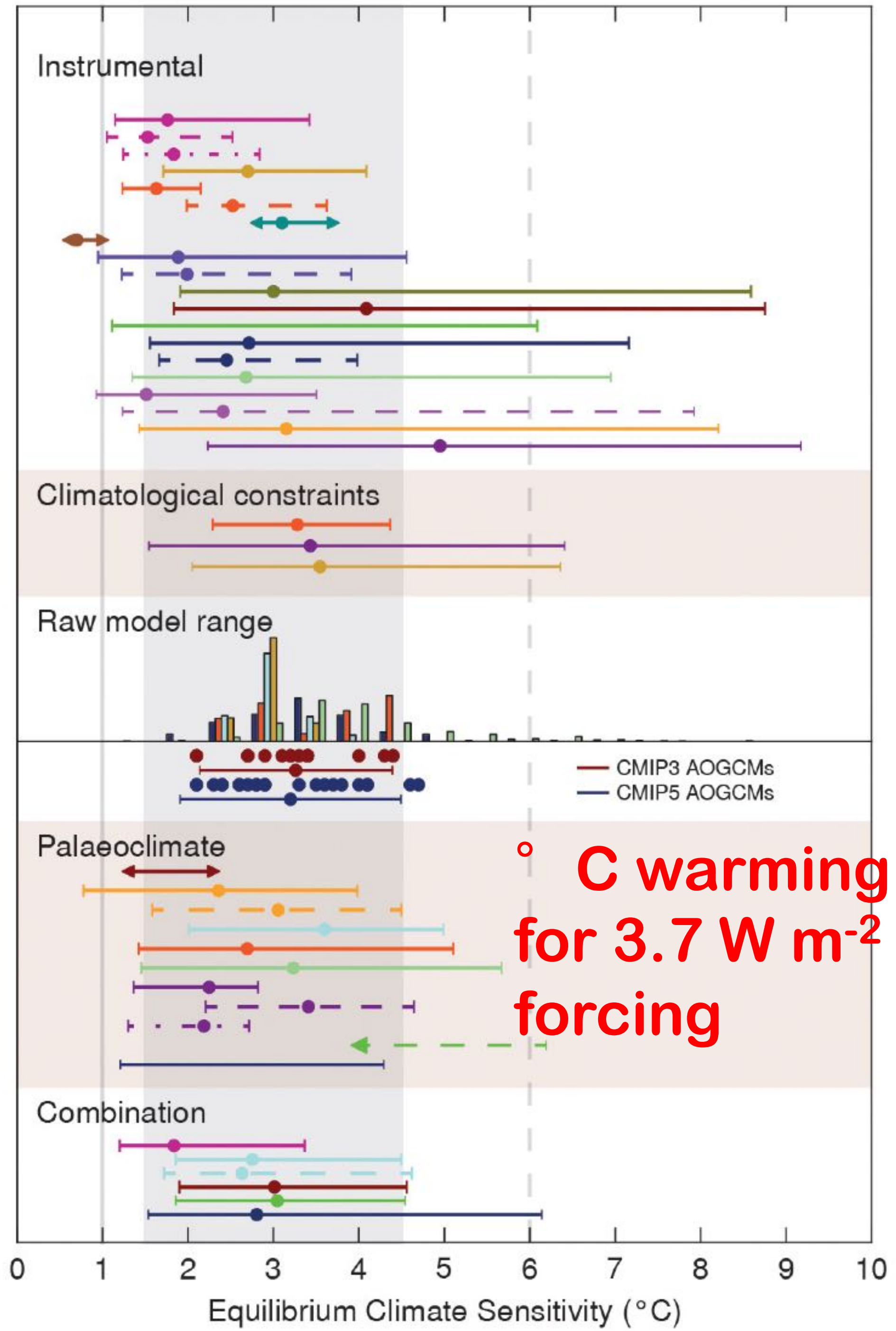

# Balloons, Satellites, and Surface Obs






# Hindcasts of 20th Century

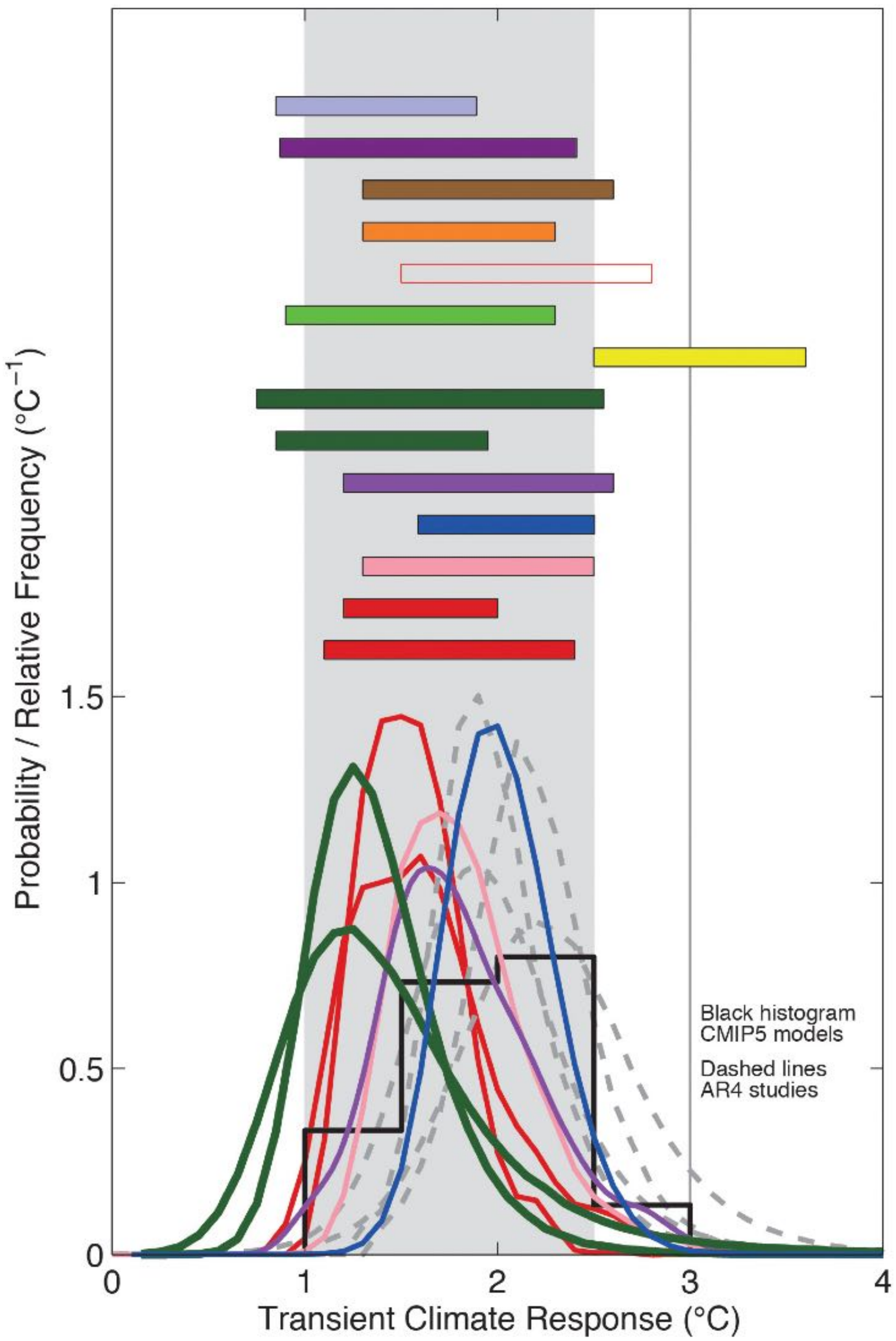
- Models without greenhouse forcing don't predict enough warming
- Models with only greenhouse forcing predict too much warming
- Models with all forcing do a good job of predicting past climate change




° C warming for 3.7 W $m^{-2}$ forcing

# Equilibrium Climate Sensitivity

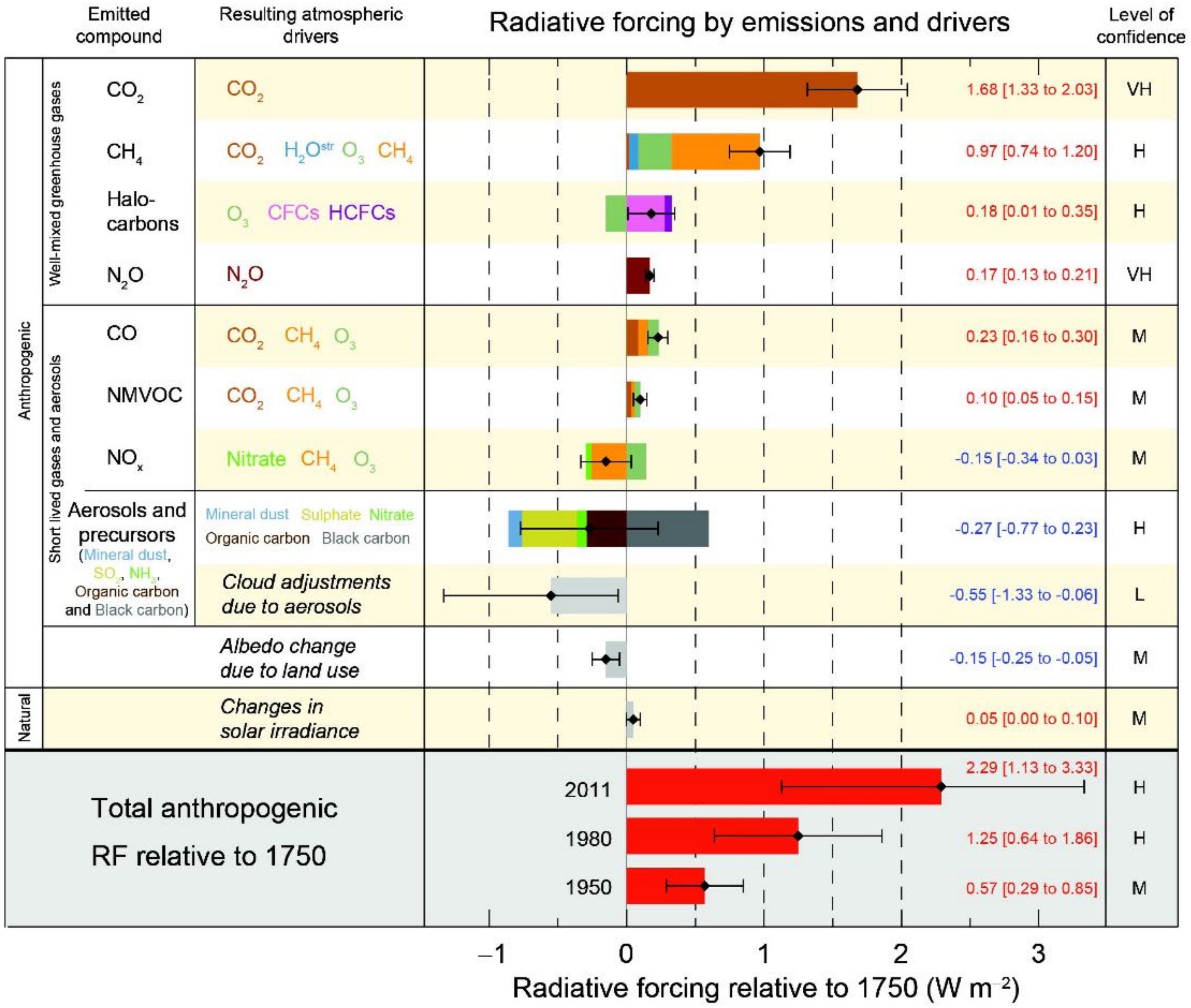
- Surface warming required to re-establish thermal equilibrium at top of atmosphere
- Many lines of paleoclimate evidence and most GCMs find about 3 ° C



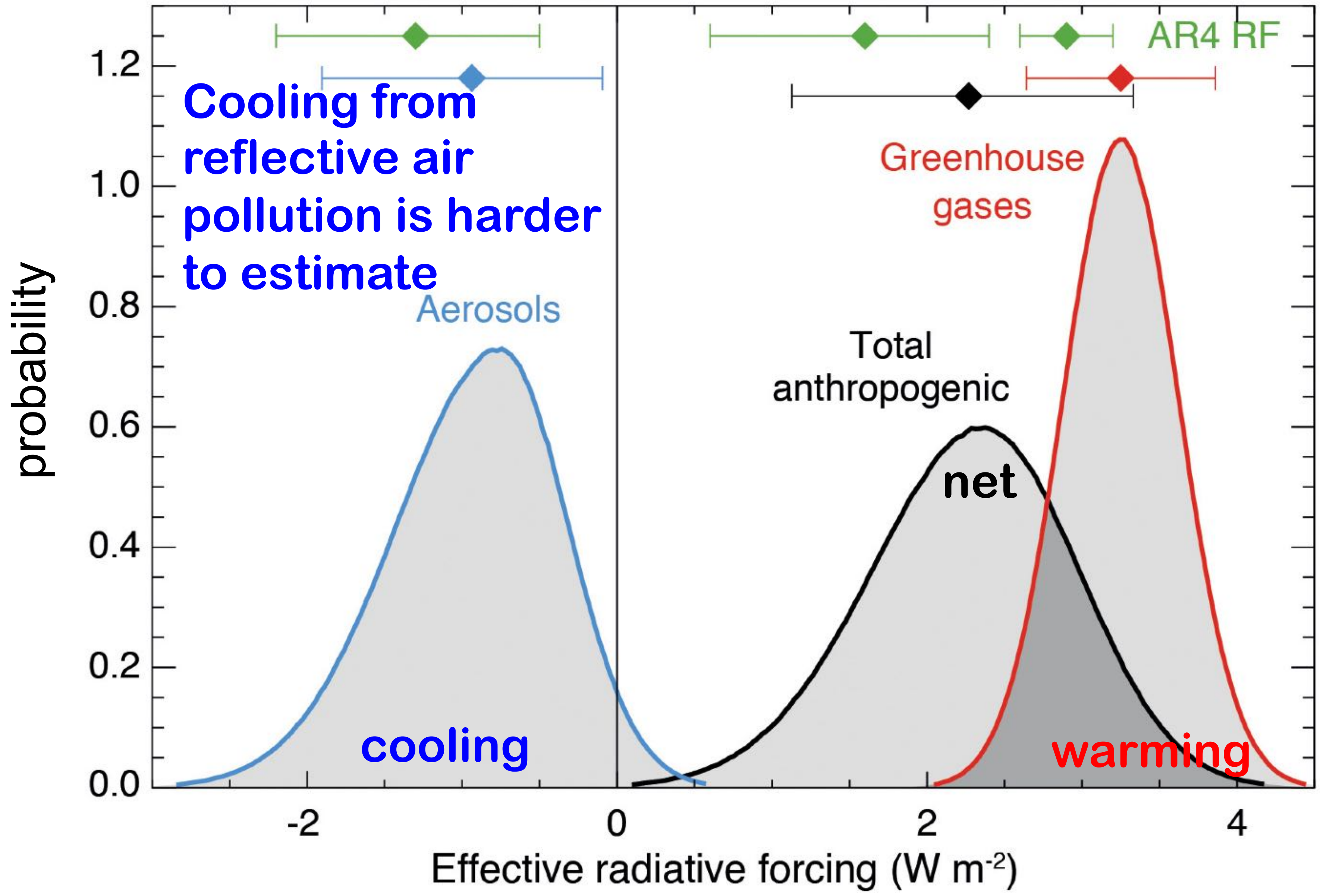

# Transient Climate Response

- **Warming takes a long time because much of the heat is absorbed by the oceans**
- **TCR is warming at time when $CO_2$ reaches 560 ppm**
- **Models and obs show TCR ~ 1 to 2.5 ° C**

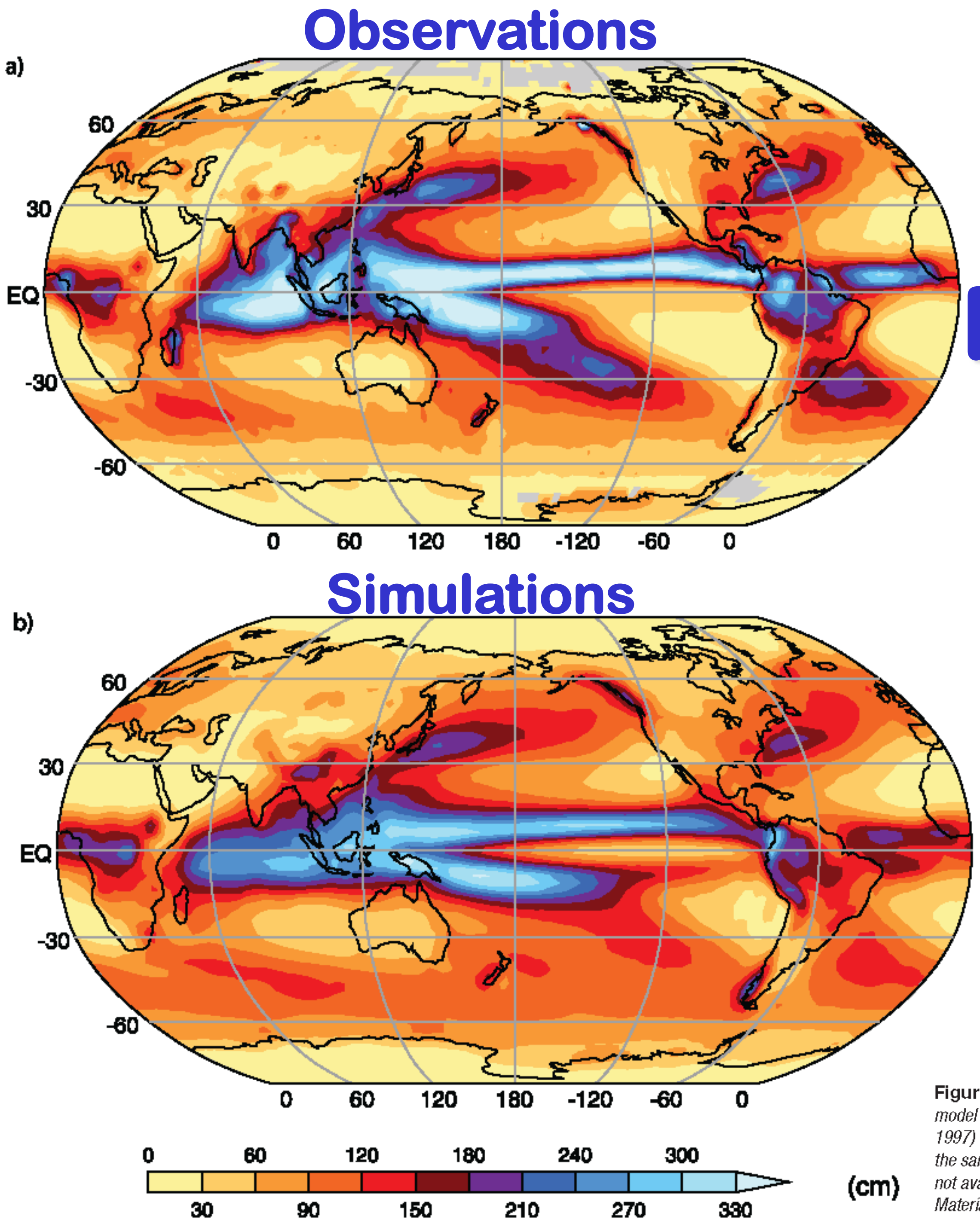
# Modern Climate Forcing



# Anthropogenic Forcing



# Model Evaluation: Precipitation




- General patterns and magnitudes very well simulated
- Problems with mountain ranges and some finer-scale patterns

**Figure 8.5.** *Annual mean precipitation (cm), observed (a) and simulated (b), based on the multi-model mean. The Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) observation-based climatology for 1980 to 1999 is shown, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI. In (a), observations were not available for the grey regions. Results for individual models can be seen in Supplementary Material, Figure S8.9.*

# Future Climate Scenarios

# Climate Scenario Workflow

## People
Demography/Population
Economic Development
Policy
CO2 & GHG Emissions

## Radiation
CO2 & other gases
Solar radiation in
IR radiation out

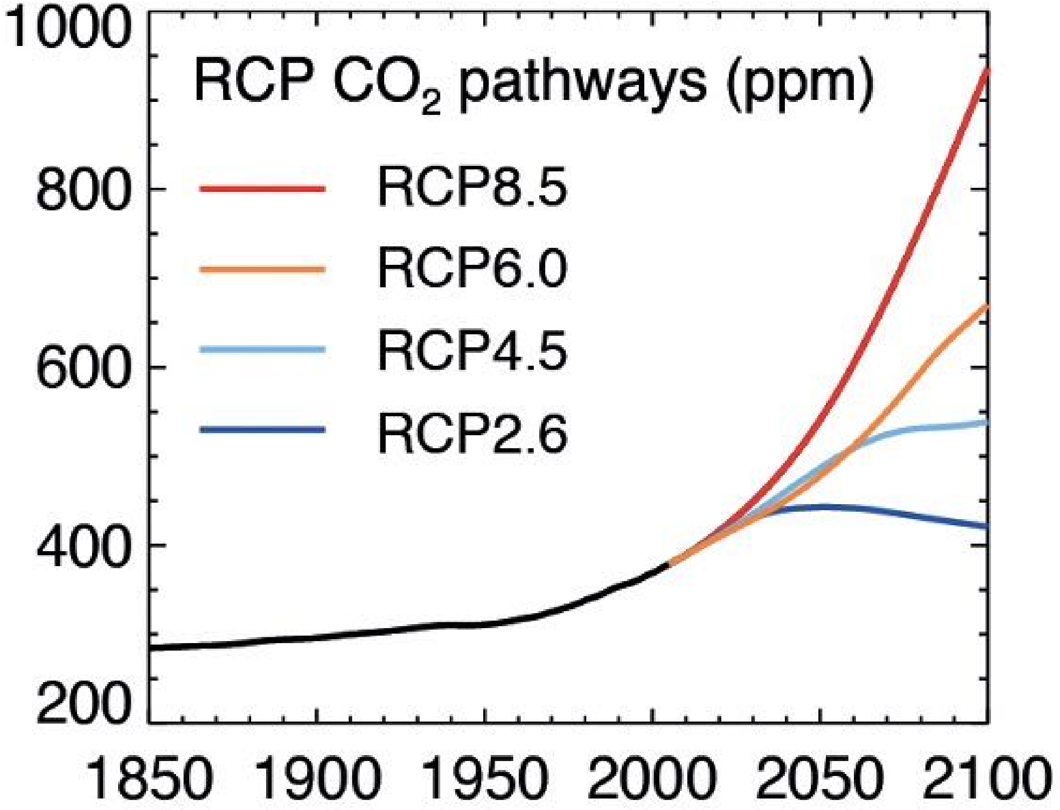
## Climate
Atmosphere
Oceans
Land

## Impacts
Sea levels
Agriculture
Economic damages

# Scenario Names

- Called **Representative Concentration Pathway ("RCP")** in IPCC AR5
  - Future pathway of $CO_2$ & other greenhouse gases that derived by social scientists from a set of self-consistent assumptions
  - Named for radiative forcing (W $m^{-2}$) in 2100
  - Each requires emissions to peak at different years in the future

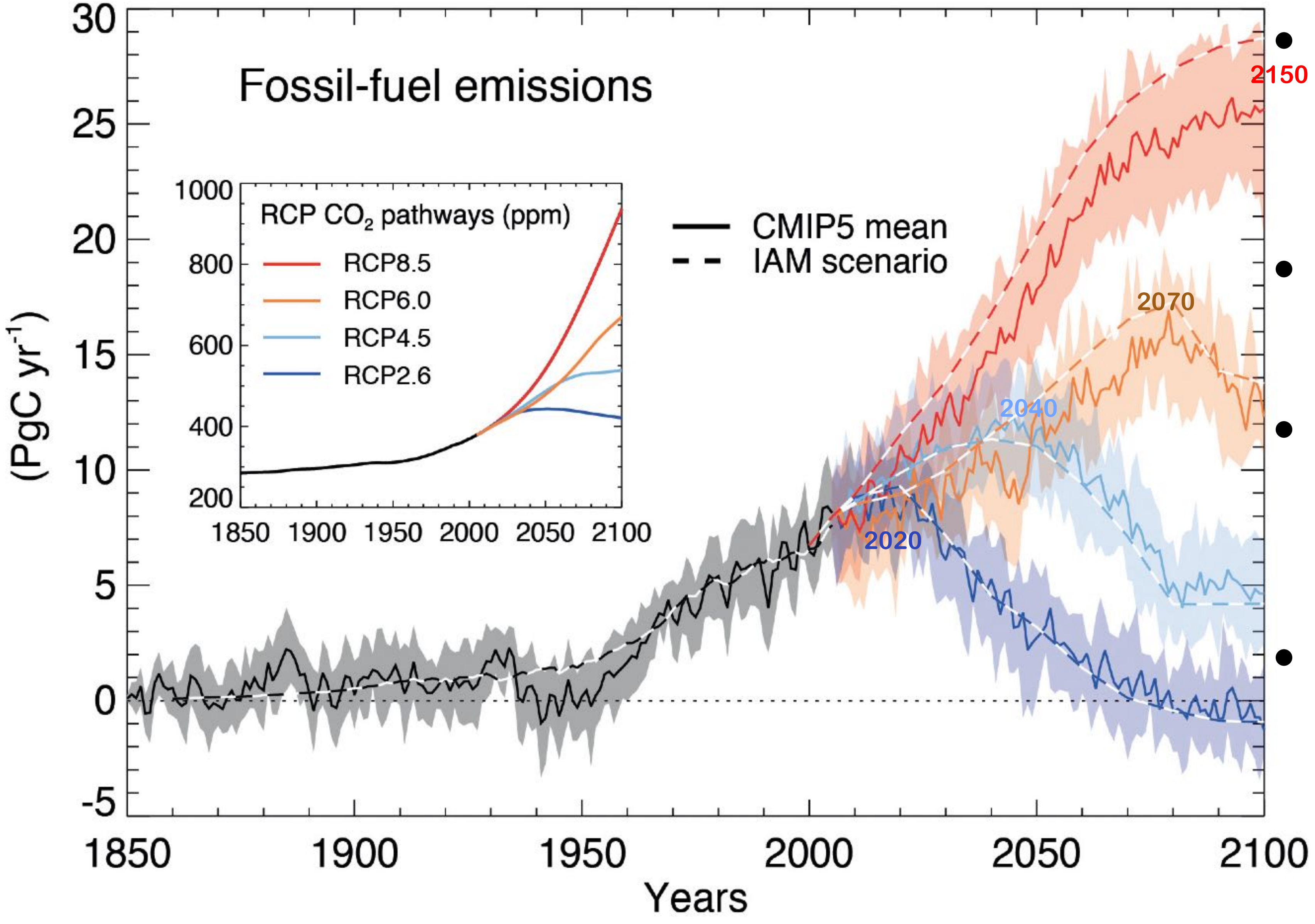
"RCP 4.5"




- Renamed **Shared Socioeconomic Pathways ("SSP")** in IPCC AR6
  - SSPs have two numbers: warming (Celsius) and forcing (W $m^{-2}$) in 2100

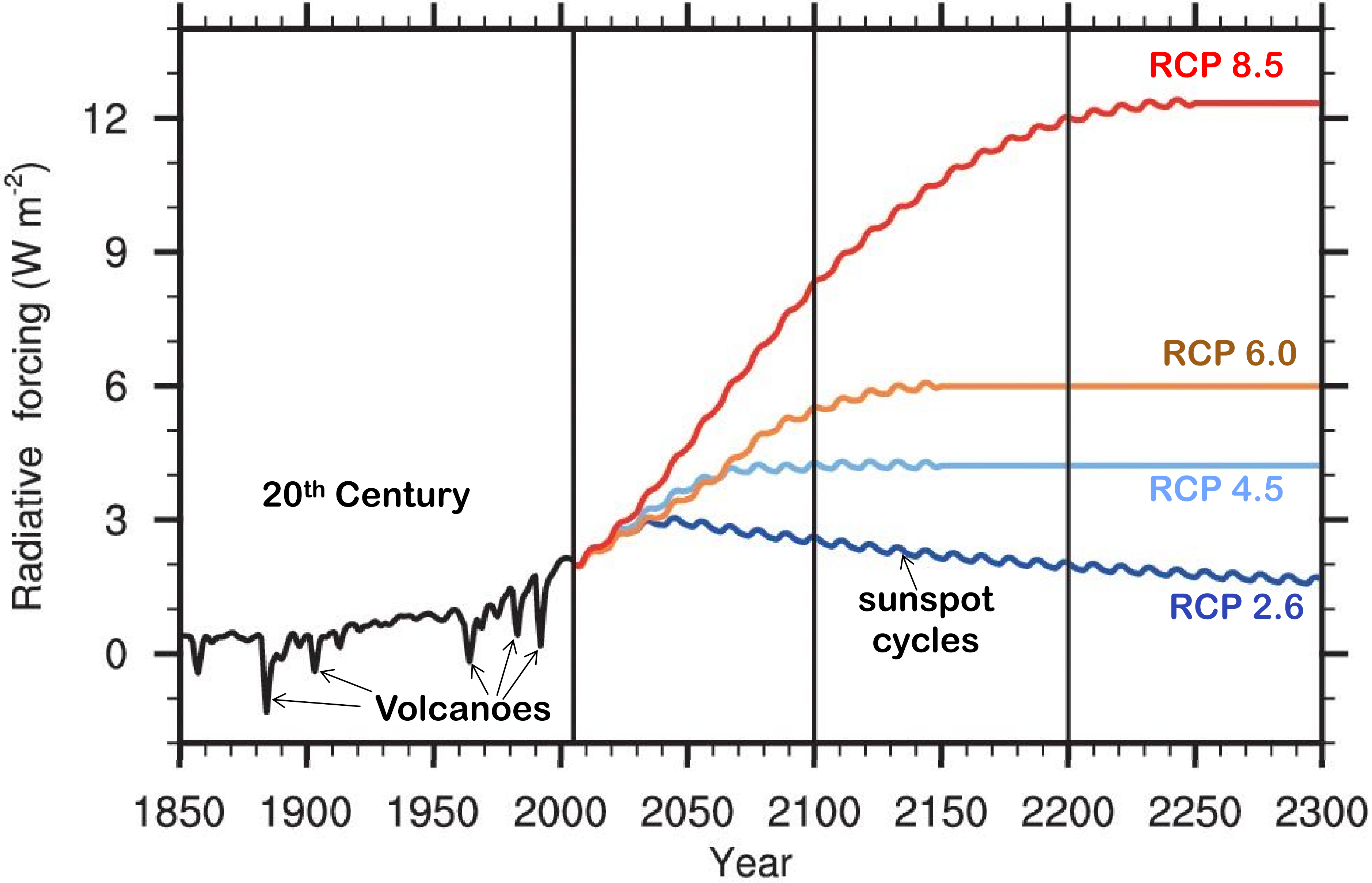
"SSP3-45"

# Emission Scenarios




- Not predictions … "what if" experiments
- None are more or less likely
- Depends on economics and policy (politics)
- Emissions peak in
  - 2020 (RCP2.6)
  - 2040 (RCP4.5)
  - 2070 (RCP6.0)
  - 2150 (RCP8.5)

# Radiative Forcing



# Global Warming