Climate Models

How do they work?
What can (and can't) they tell us about the future?

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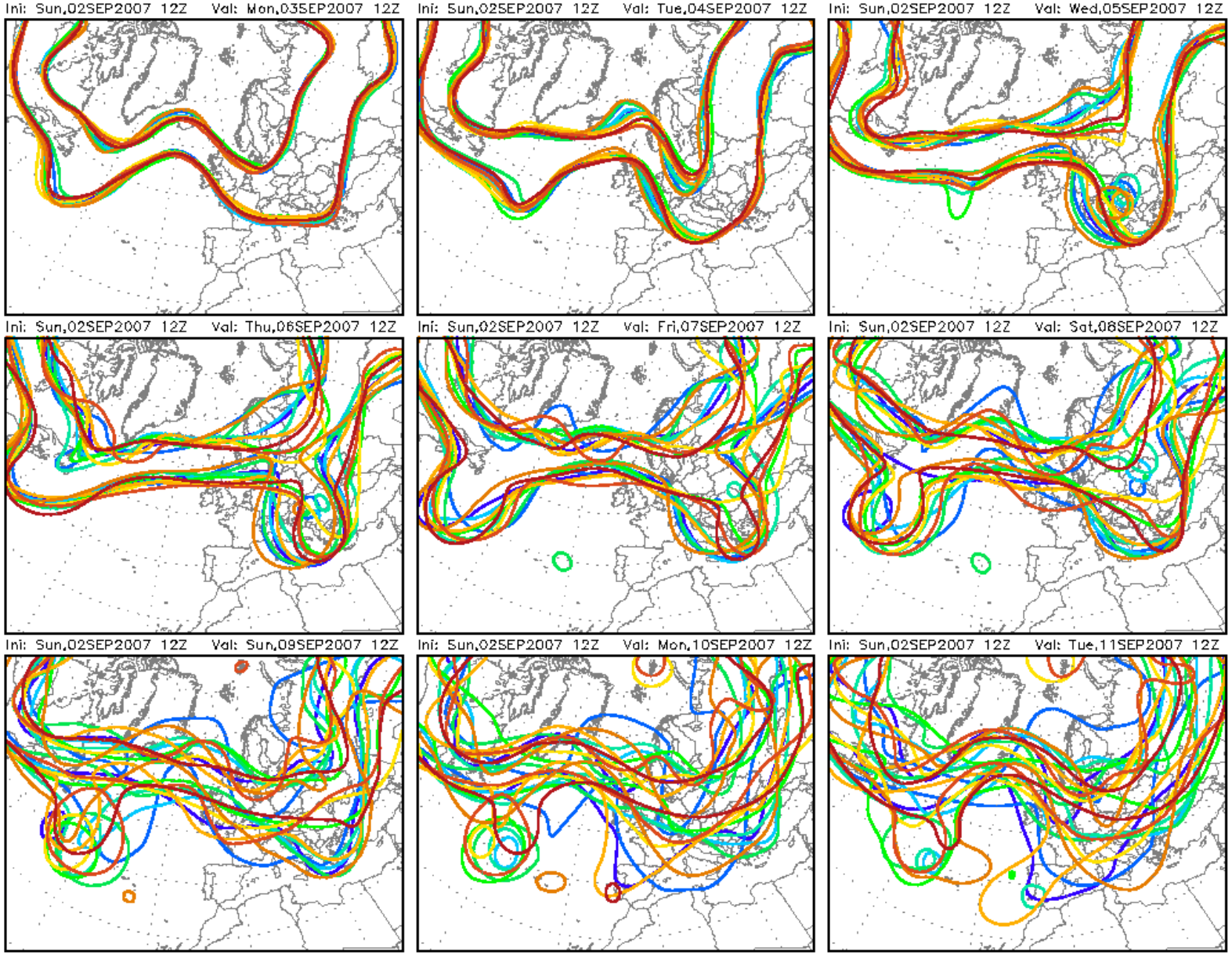
Atmospheric Science, CSU

Climate Models

- What is a "model"
- What does it mean to model the climate?
- How do modern climate models work?
- How good are they?
- What can they tell us?
- What can't they tell us?

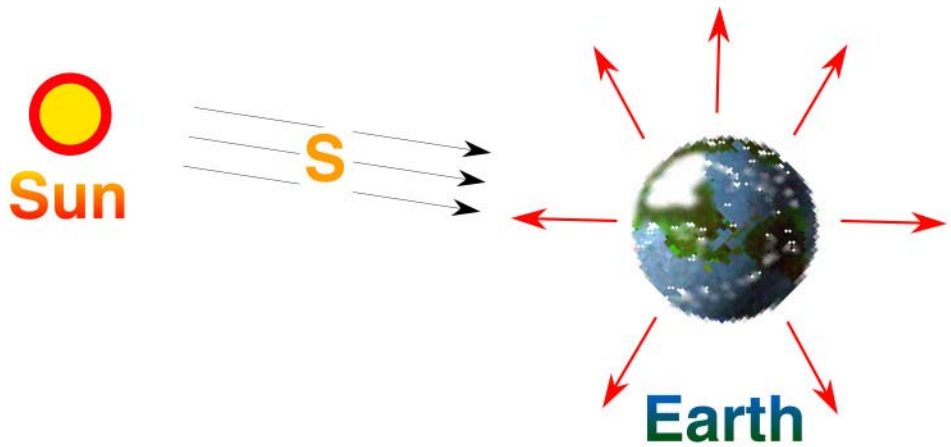
Sensitivity to Initial Conditions



Climate Forcing

- Changes in climate often reflect changes in forcing, as amplified or damped by climate feedbacks
  - Diurnal cycle
  - Seasonal cycle
  - Ice ages
  - Response to volcanic aerosol
  - Solar variability
  - Greenhouse forcing
- *If forcing is sufficiently strong, and the forcing itself is predictable, then the response of the climate can be predictable too!*

Planetary Energy Balance



Energy In = Energy Out

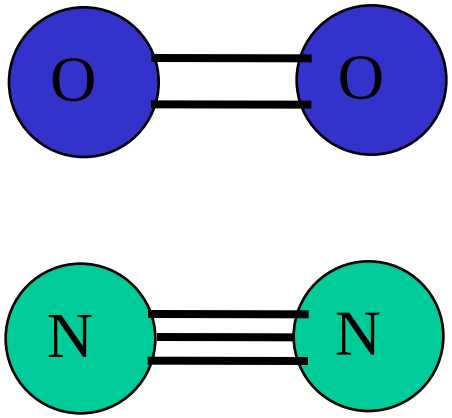
$$S(1-\alpha)\pi R^2 = 4\pi R^2 \sigma T^4$$

$$T \approx -18^{\circ}\mathrm{C}$$

But the observed T_s is about 15° C

Dancing Molecules and Heat Rays!

- Nearly all of the air is made of oxygen (O_2) and nitrogen (N_2) in which two atoms of the same element share electrons

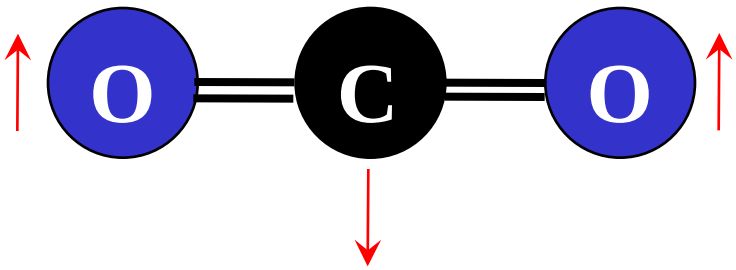


- Infrared (heat) energy radiated up from the surface can be absorbed by these molecules, but not very well

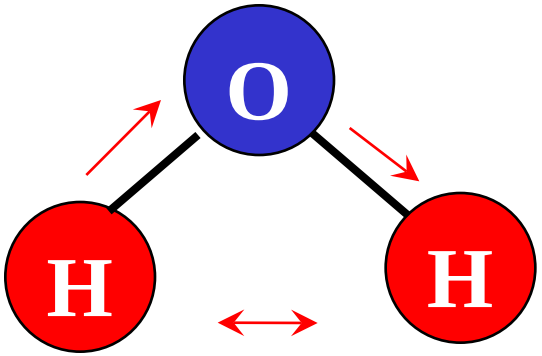
Diatomic molecules can vibrate back and forth like balls on a spring, but the ends are identical

Dancing Molecules and Heat Rays!

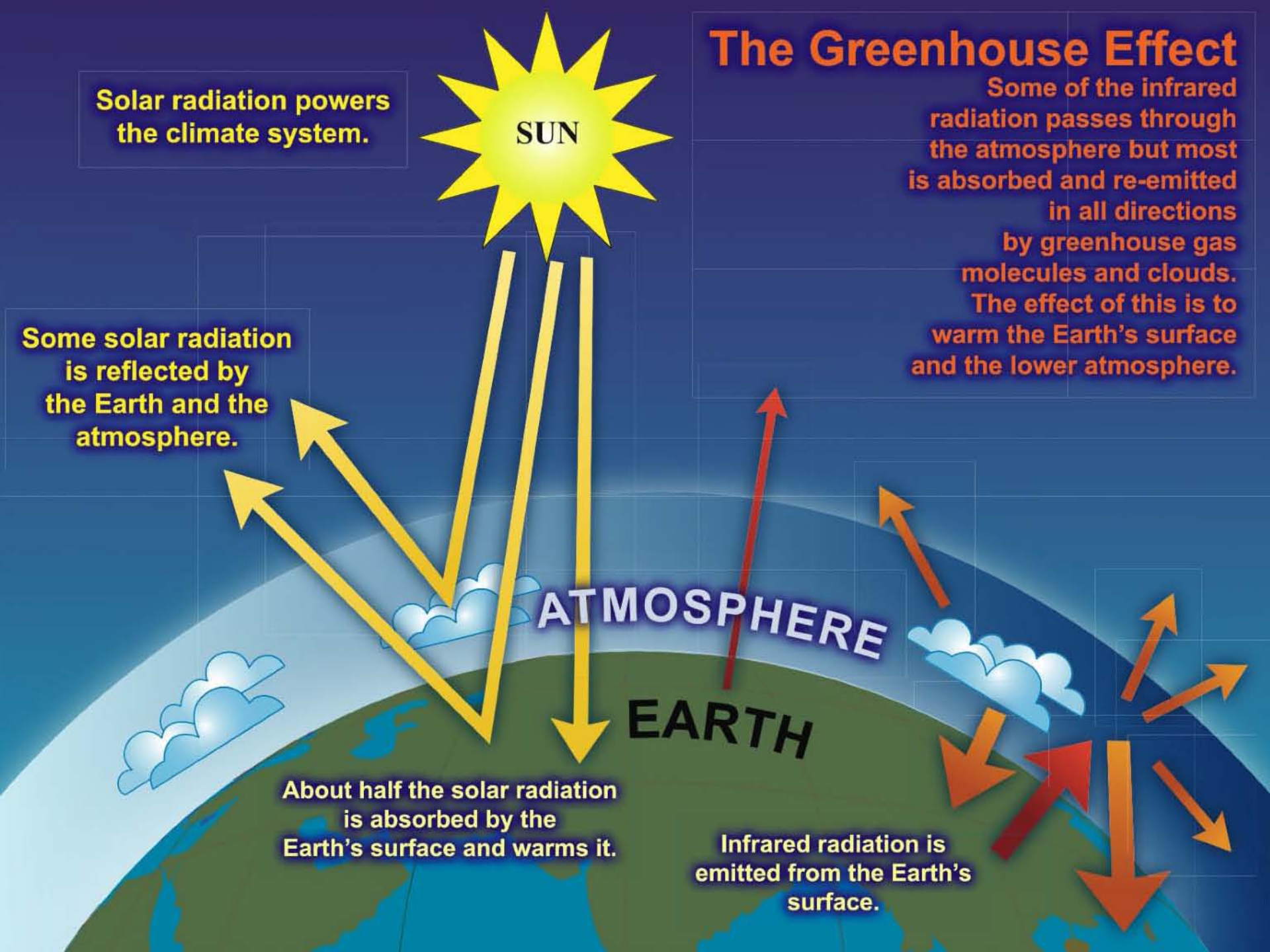
- Carbon dioxide (CO_2) and water vapor (H_2O) are different!



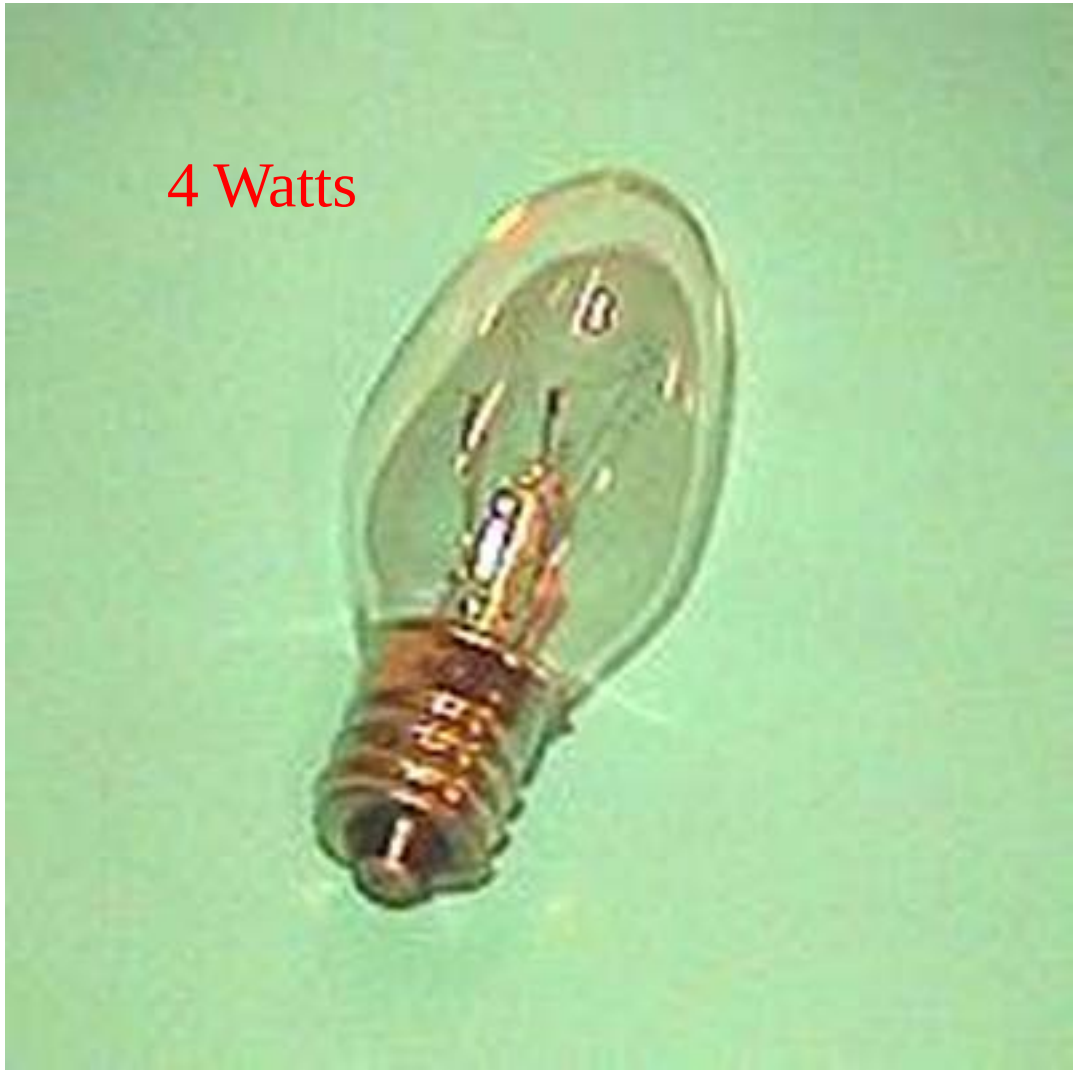
- They have many more ways to vibrate and rotate, so they are very good at absorbing and emitting infrared (heat) radiation



Molecules that have many ways to wiggle are called "Greenhouse" molecules


The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation powers the climate system.
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

Common Sense



- Doubling CO_2 would add 4 watts to every square meter of the surface of the Earth
- Doing that would make the surface warmer
- This was known before 1900!

Climate Modeling "on the Back of an Envelope"

$$S_0(1-\alpha)\pi r^2 = \varepsilon\sigma T_S{}^4(4\pi r^2)$$

$$S_0(1-\alpha) = 4\varepsilon\sigma T_S{}^4$$

Note redefinition of ε!

Assume only ε changes (no feedbacks!)

Differentiate, apply chain rule

$$0 = 4\Delta\varepsilon\sigma T_S{}^4 + 4\varepsilon(4\sigma T_S{}^4)$$

$$\boxed{\Delta T_S = -\frac{T_S}{4}\frac{\Delta\varepsilon}{\varepsilon}}$$

Change in surface temp for a given change in effective atmospheric emissivity (~CO_2)

Envelope stolen from Dave Randall

Envelope Climate Model (cont'd)

$$\Delta T_S = -\frac{T_S}{4}\frac{\Delta\varepsilon}{\varepsilon}$$

Plug in numerical values

$$\varepsilon\sigma T_S^{\,4} = 240 \text{ W m}^{-2}$$

(from satellite data)

$$(\Delta\varepsilon)(\sigma T_S^{\,4}) = -4 \text{ W m}^{-2}$$

(for 2 x CO_2 from radiative transfer)

$$\frac{\Delta\varepsilon}{\varepsilon} = -\frac{4}{240}$$

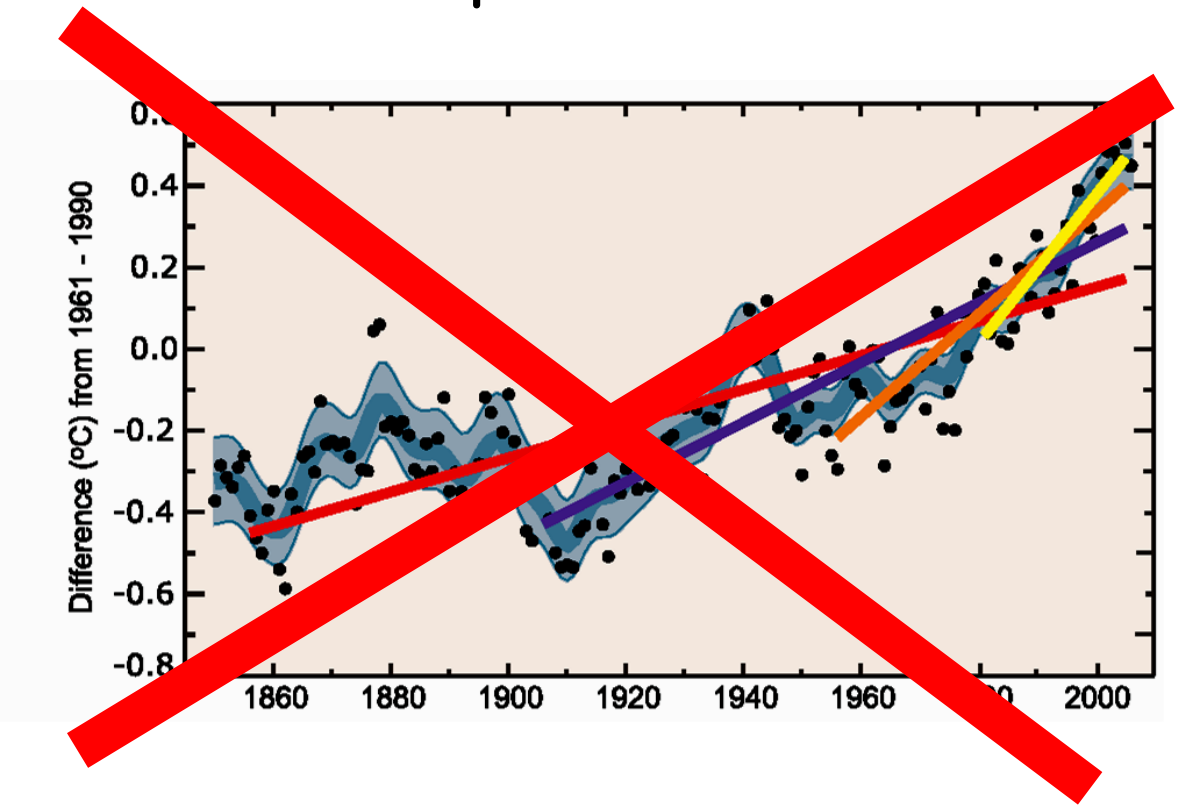
$$T_s = 288 \text{ K}$$

$$\Delta T_S = -\frac{288K}{4}\left(-\frac{4}{240}\right) = 1.2K$$

Envelope Based on Arrhenius, 1897

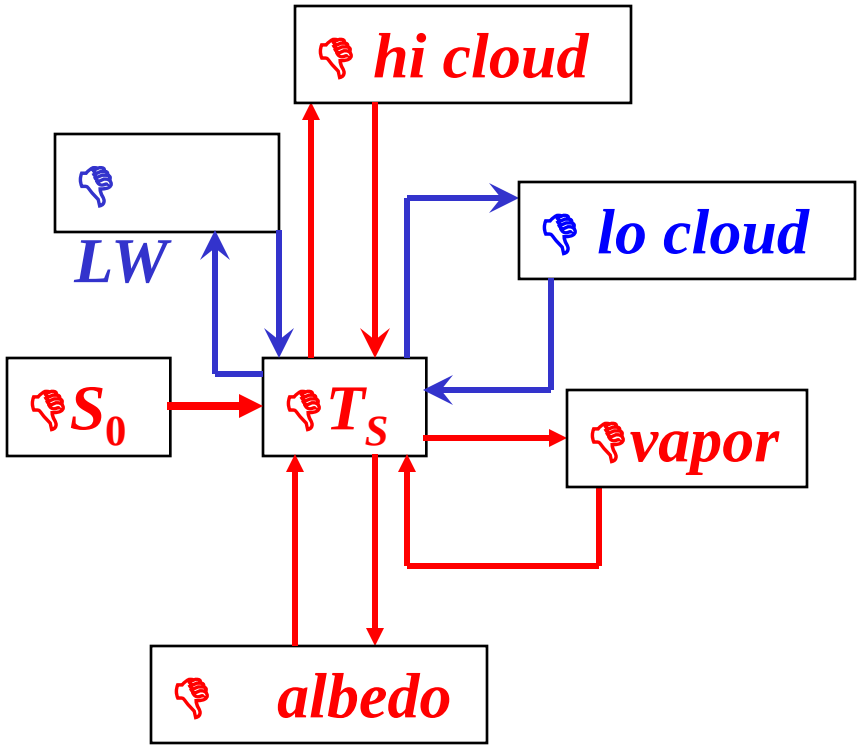
Common Misconception #1

"Expectations of future warming are based on extrapolation of recent warming trends"



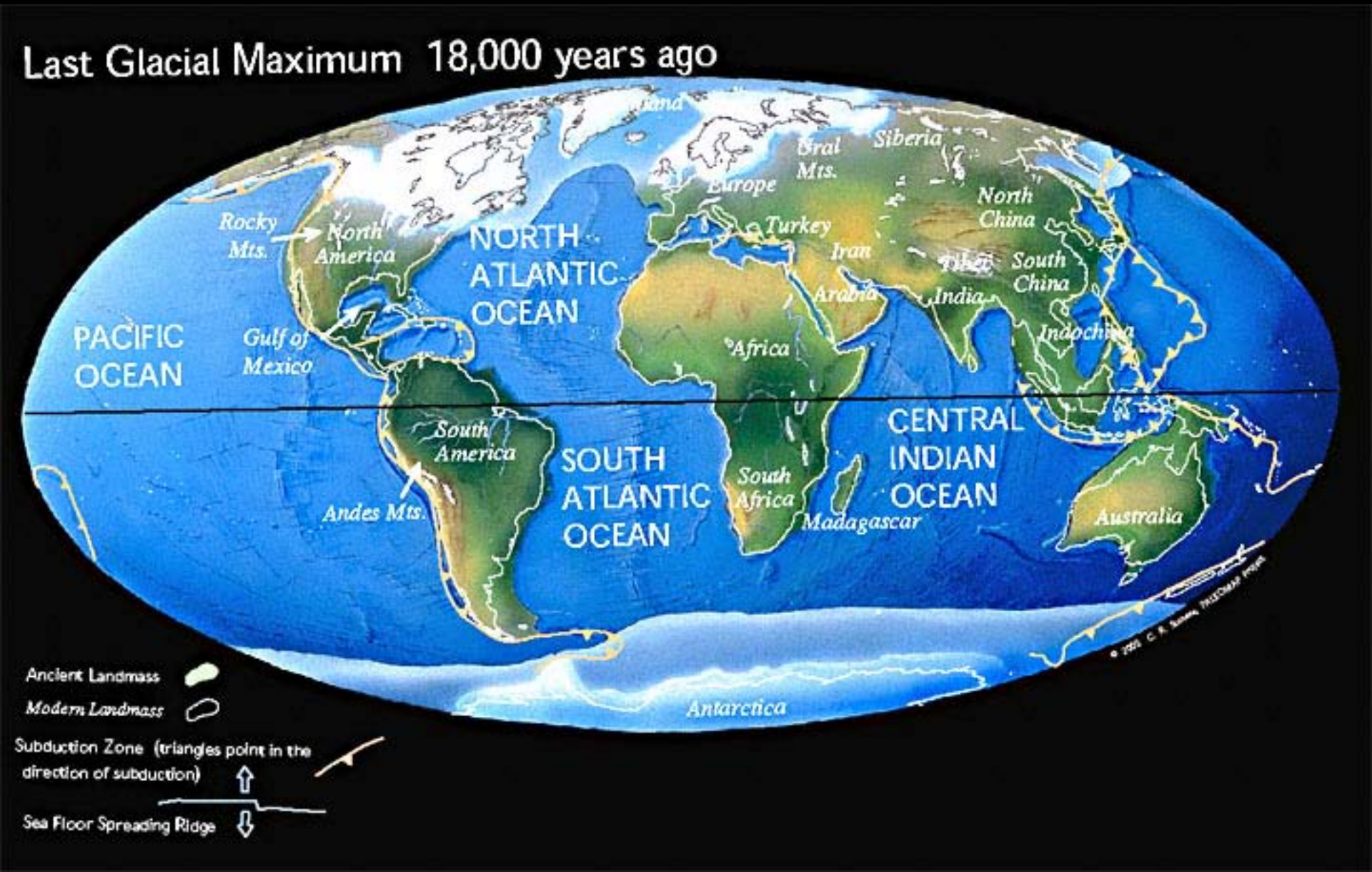
WRONG! They are based on the idea that when we add energy to the surface, it will warm up

Climate Feedback Processes



- Positive Feedbacks (amplify changes)
  - Water vapor
  - Ice-albedo
  - High clouds
- Negative feedbacks (damp changes)
  - Longwave cooling
  - Low clouds

Learning from the Past



Estimating Total Climate Sensitivity

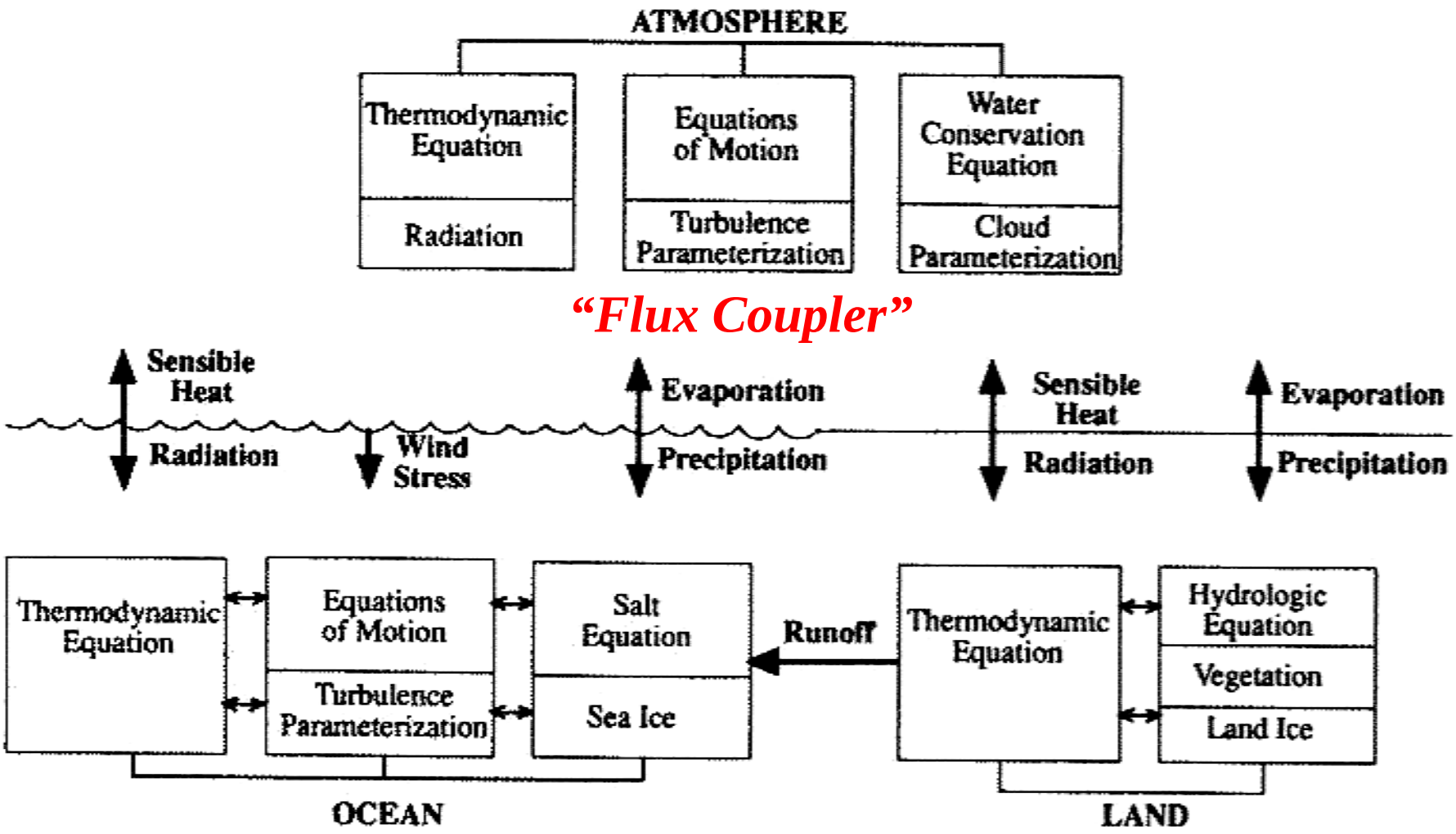
- At the Last Glacial Maximum (~ 18k years ago) surface temp ~ 5 ° C colder
- CO_2 was ~ 180 ppm (weaker greenhouse, 3.7 W m^{-2} more LW↑)
- Brighter surface due to snow and ice, estimate 3.4 W m^{-2} more reflected solar ↑

$$\lambda = \frac{\Delta T_S}{\Delta F} = \frac{T_S(now) - T_S(then)}{F(now) - F(then)}$$

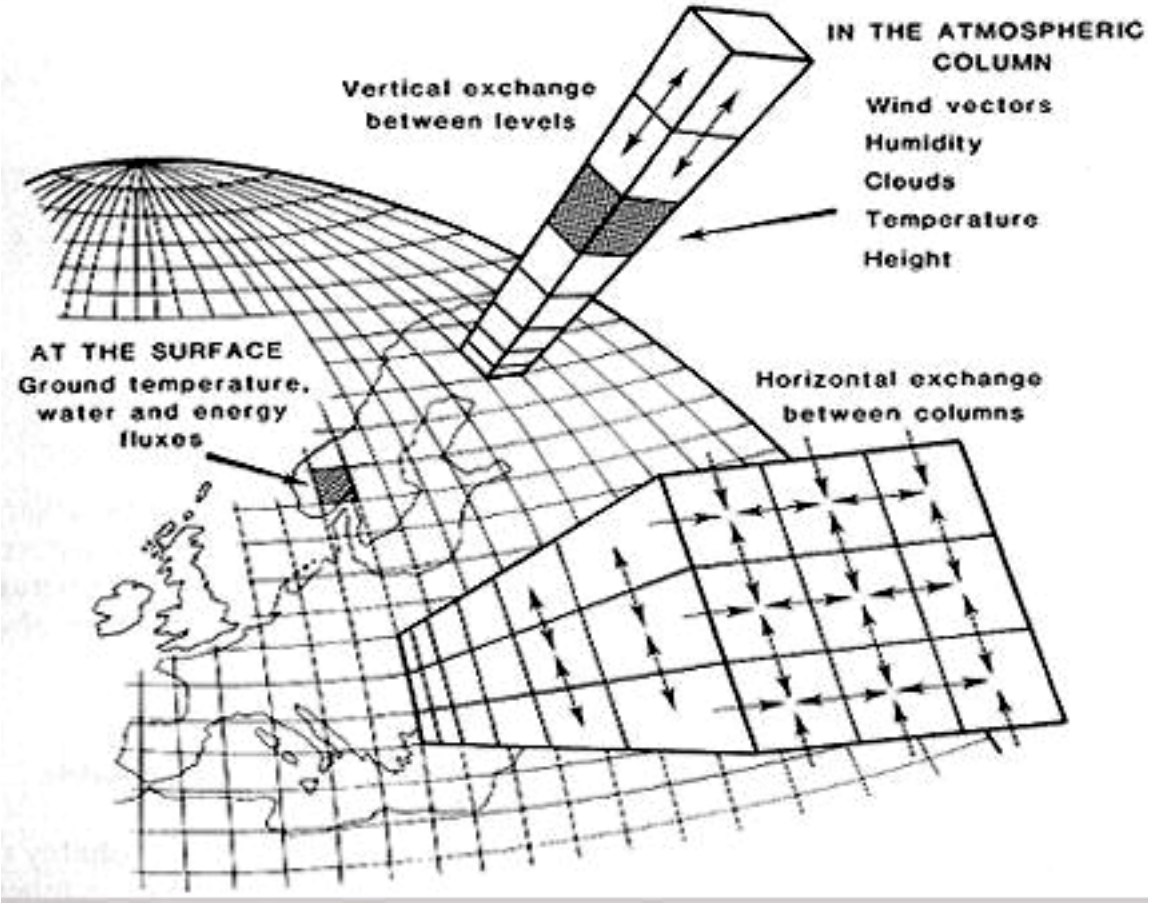
$$= \frac{5K}{(3.7 + 3.4)Wm^{-2}} = 0.70 \frac{K}{Wm^{-2}}$$

Almost 3× as sensitive as suggested by Arrhenius in 1897 …
Other feedbacks must be going on as well

Climate Model Structure

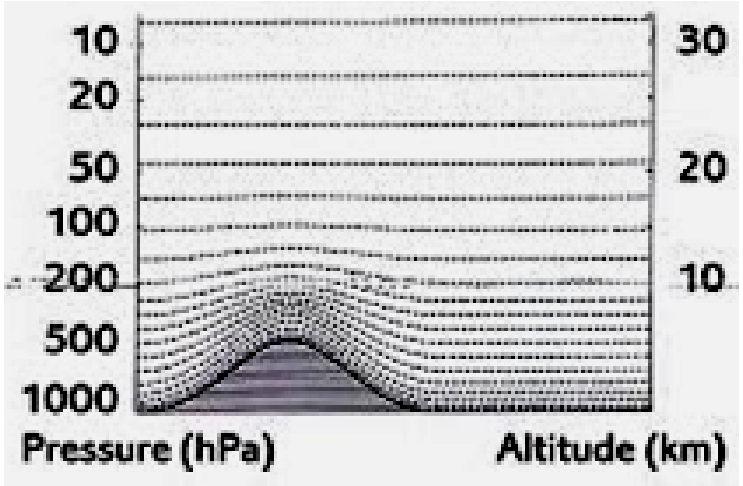


Climate Model Grids



Typical climate model
$\Delta x \sim 200$ km

Typical weather forecast model
$\Delta x \sim 40$ km



Climate Model Ingredients

- Atmosphere model
- Ocean model
- Land-surface model
- Sea ice model
- Coupler

Partial differential equations

Spherical geometry

Discretization methods

Time steps of a few minutes

Very fast computers

About 40 models worldwide

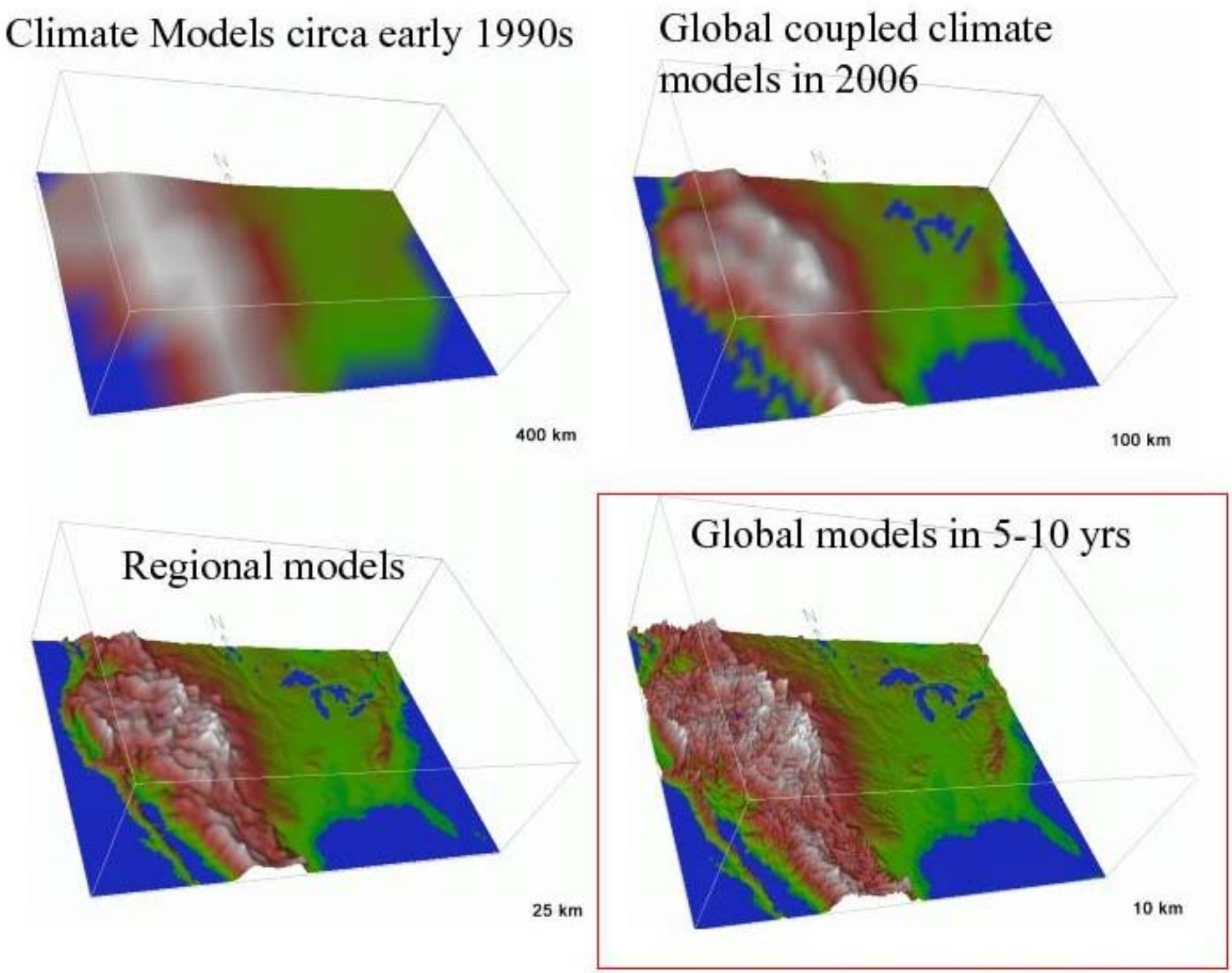
Thing #2:

Atmosphere

- Mass
- Momentum
- Energy
- Moisture
- Carbon, ozone and other chemical species

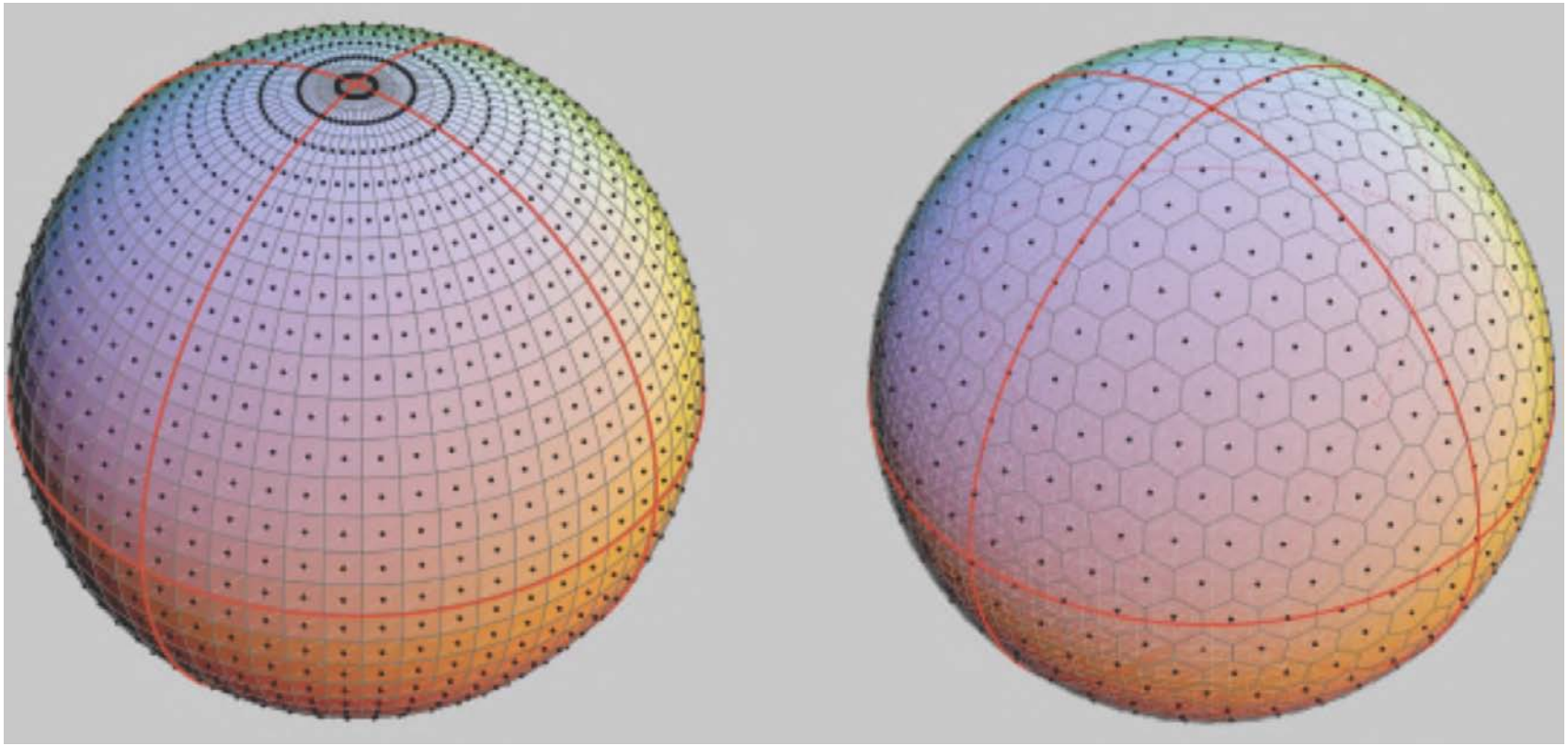
- Advection
- Pressure-gradient
- Rotation
- Solar radiation
- Terrestrial radiation
- Turbulence
- Moist convection
- Phase changes and other "microphysical" processes
- Momentum transfer by small-scale buoyancy waves

Topography at Different Resolutions



Optimistic view on model-developement

Grids on a Spherical Earth!



- Must fit gridded variables on a rotating sphere
- Traditional latitude-longitude approach has severe problems with tiny cells near poles
- Geodesic approach (like a soccer ball) fixes this, but introduces very complicated math!

Thing #4:

Ocean

- Mass
- Momentum
- Energy
- Salt
- Sea ice
- Various chemical species
- Ocean biology

- Advection
- Pressure-gradient
- Rotation
- Solar radiation
- Terrestrial radiation XXX
- Turbulence
- Moist convection XXX
- Phase changes and other "microphysical" processes XXX
- Momentum transfer by small-scale buoyancy waves

Thing #5:

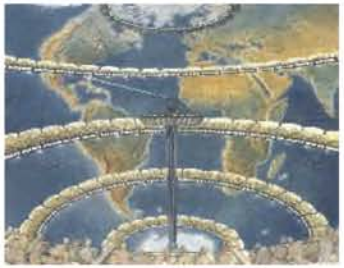
Land Surface

- Soil
- Veggies
- Energy
- Water
- Snow, etc.
- Carbon

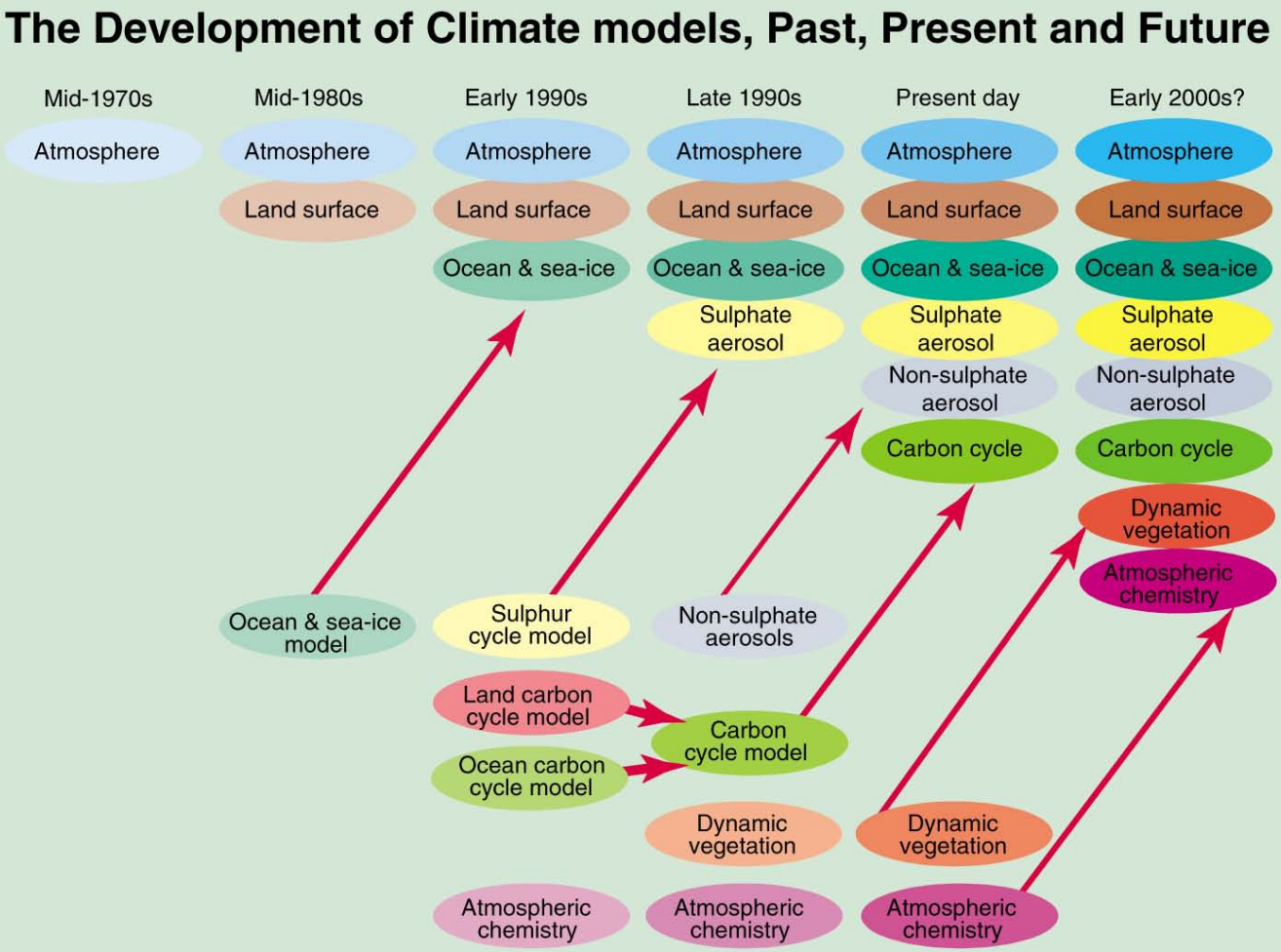
Thing #6:

History

- Richardson, 1922
- Von Neumann & Charney, 1946
- Phillips, 1956
- First global atmospheric models, 1960s
- First global coupled ocean-atmosphere models, 1970s
- Operational forecasting with global models, late 1970s
- "Serious" land-surface models, 1980s
- IPCC, 1990s



Evolution of Climate Models



Box 3, Figure 1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive climate models.

Thing #8:

An Appetite for FLOPS

NCAR

NERSC

Oak Ridge

NASA Ames

Others...

About a *million million* floating-point operations to simulate one day.

36,500 days in a century.

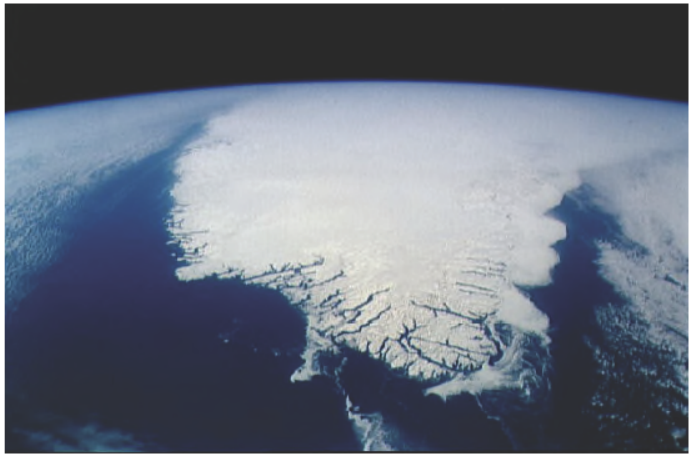
Computer power has increased by a factor of a million since I was in graduate school.

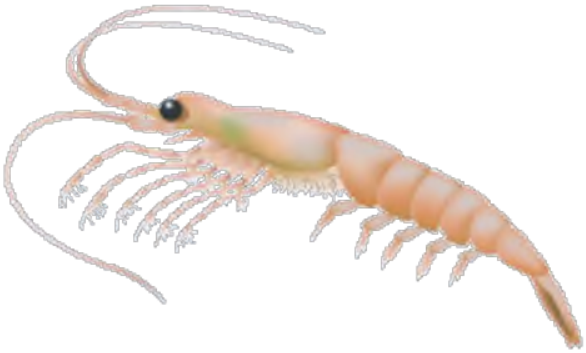
The machines are getting harder to program.

Thing #9:

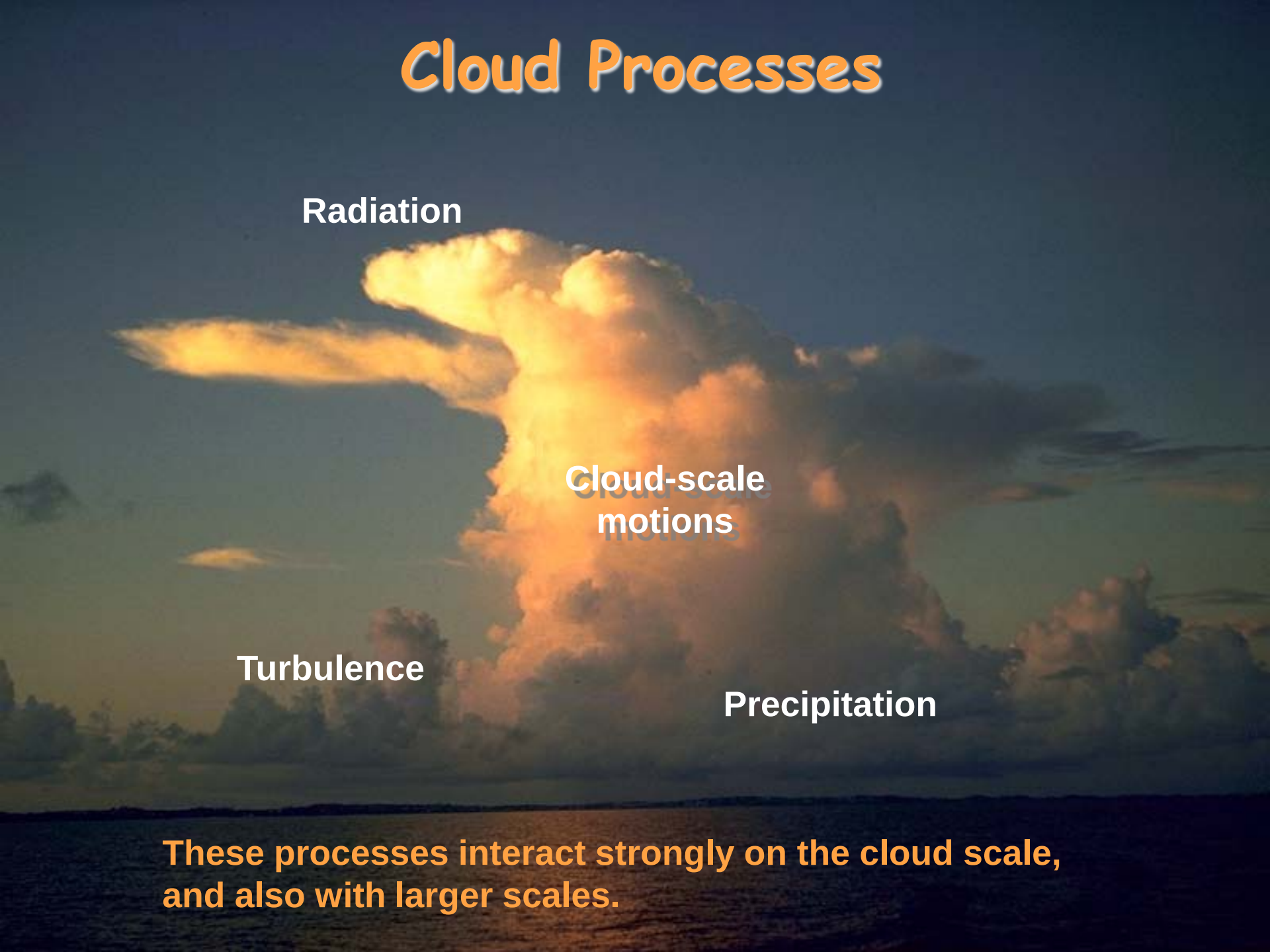
What's Missing

- Ice sheets
- Many chemical processes
- Interactive biology on the land surface
  - Seasonal greening
  - Biome change
- Interactive biology in the ocean
  - Carbon
  - Turbidity
  - Mixing



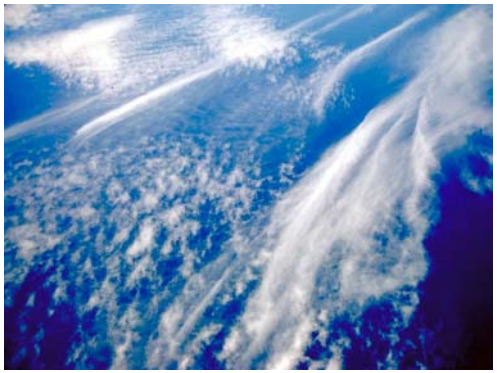


Cloud Processes



These processes interact strongly on the cloud scale, and also with larger scales.

Multiple Scales



Cloud-scale processes
Relatively well understood

→

Meso-scale statistics
Poorly understood

→

Global scale

CMMAP

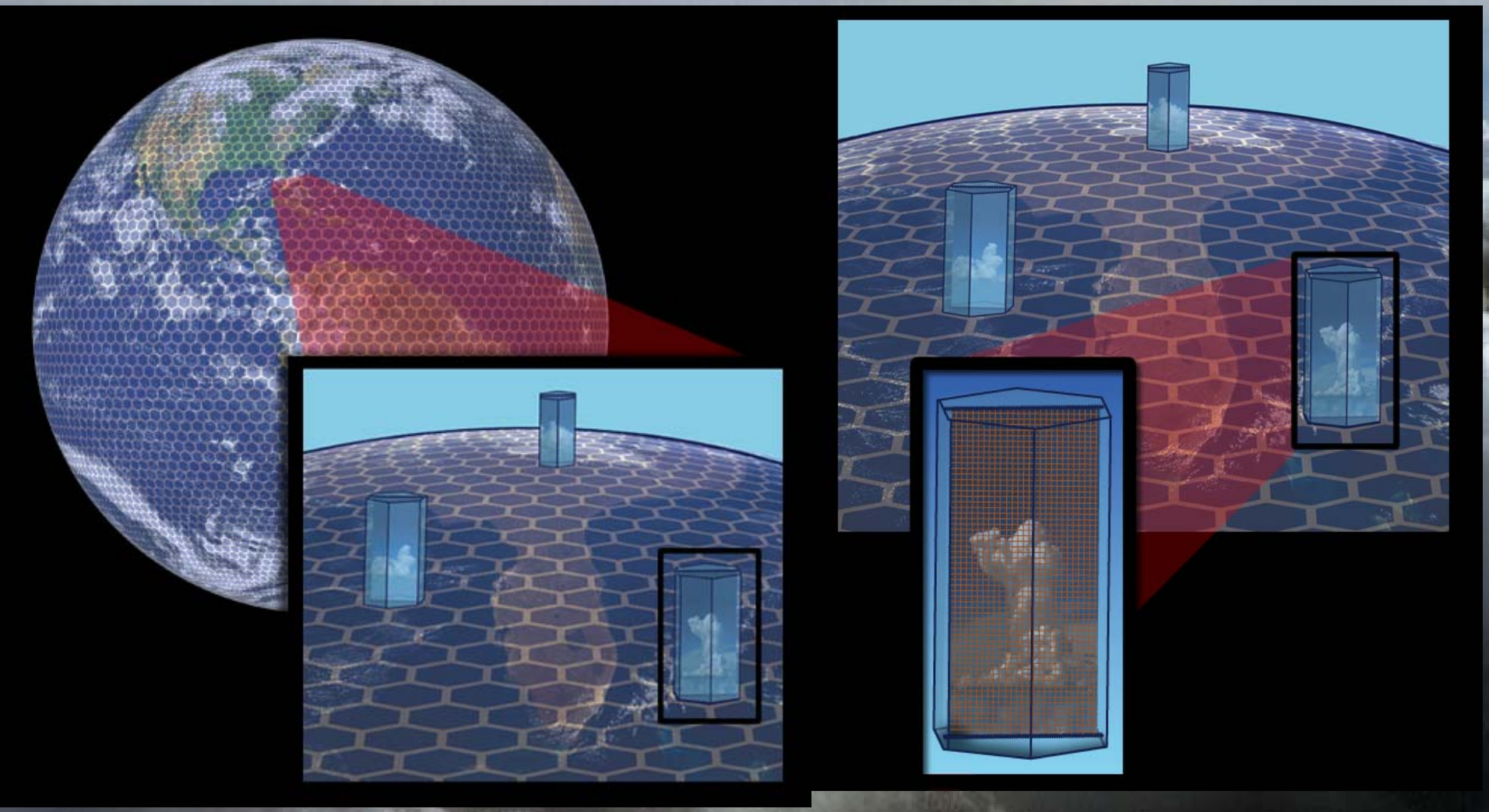
Reach for the sky.

Colorado State University

Knowledge to Go Places

http://www.cmmap.org/

CMMAP is inventing a completely new kind of climate model!

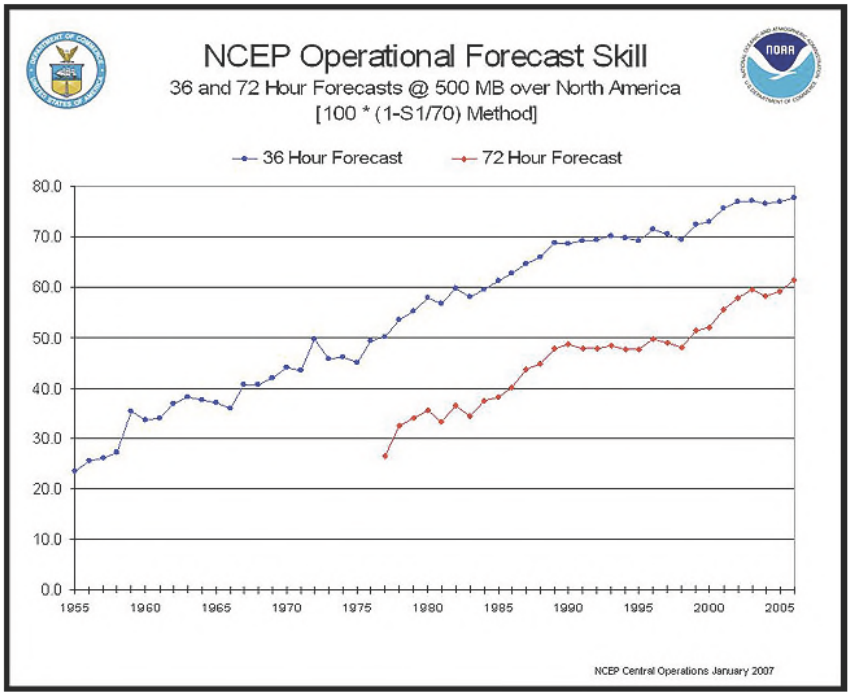


A Multiscale Modeling Framework

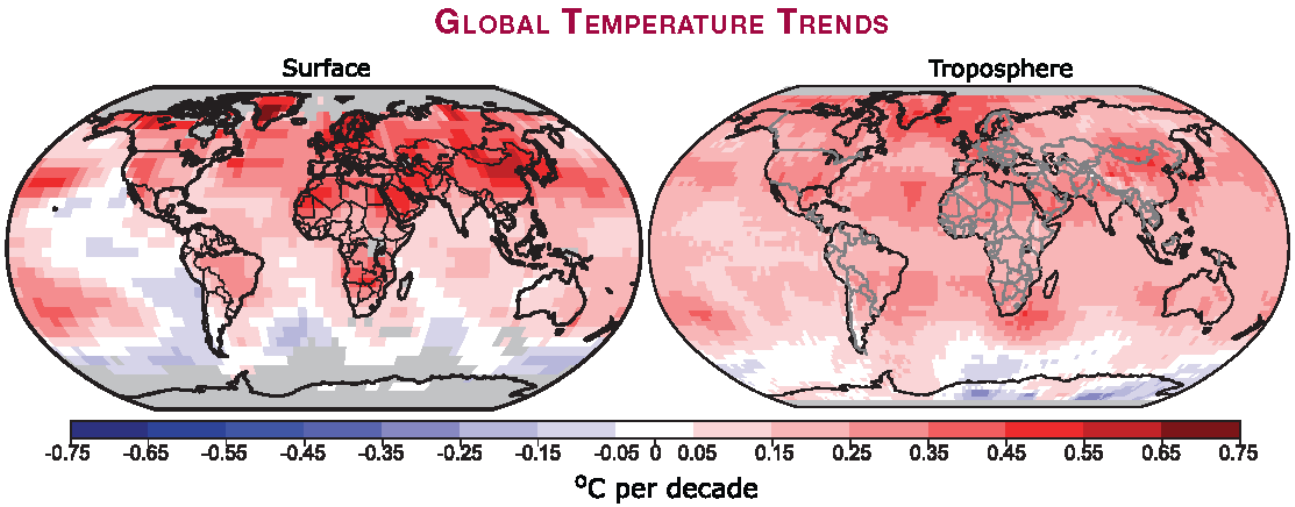
Thing #7:

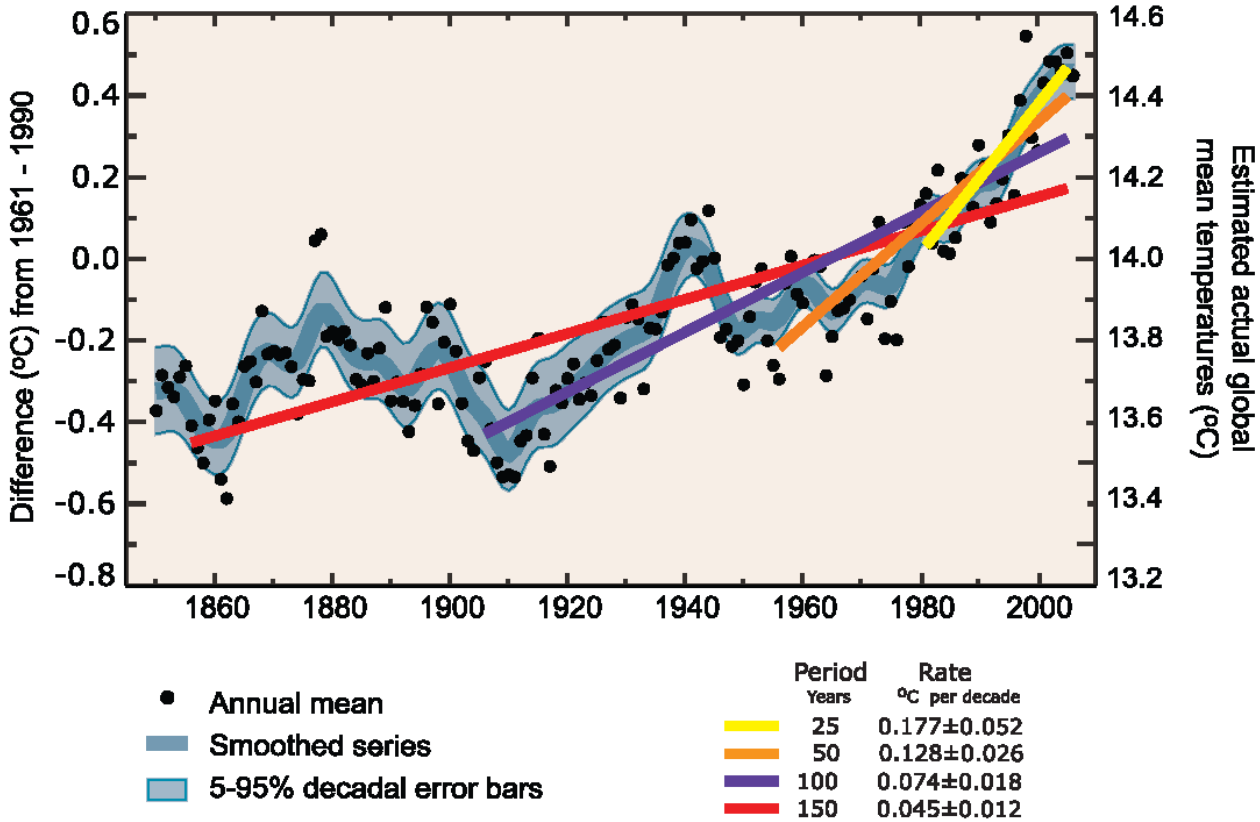
Testing the Models

- **Component-level tests**
- **Weather forecasting**
- **Simulation of the current climate**
- **Simulation of past climates**

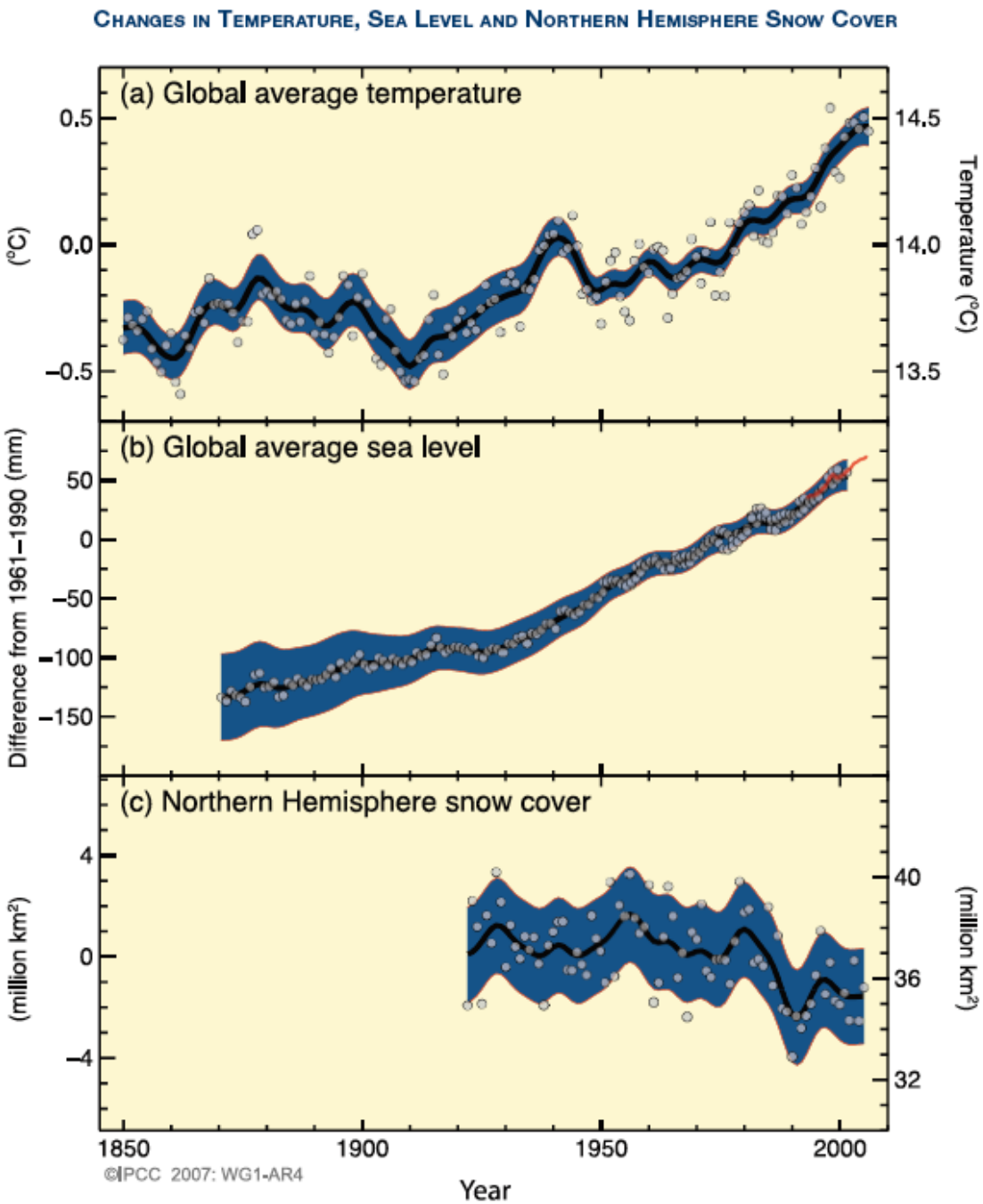


Observations



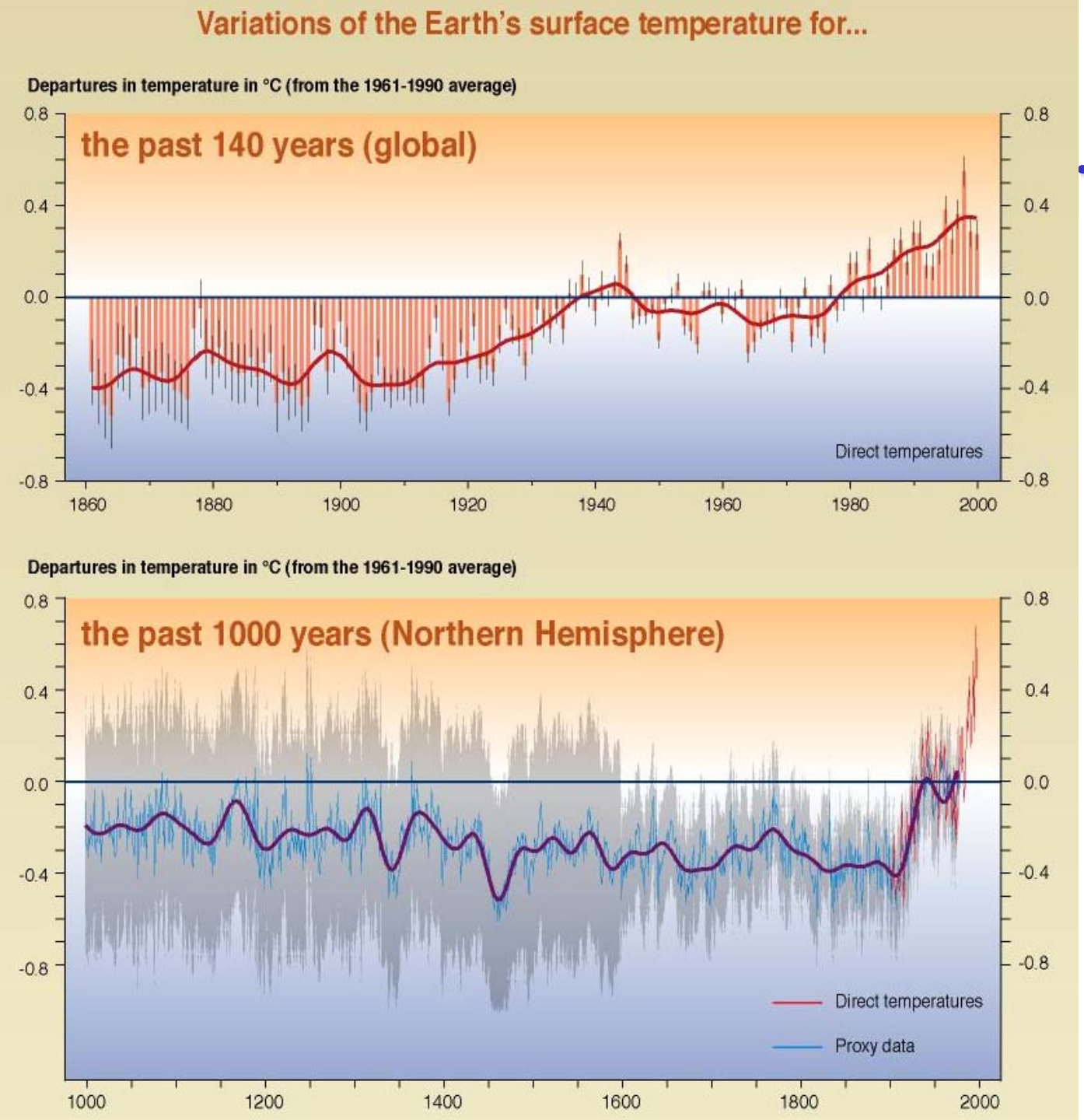


- Much stronger trend on land than ocean
- North > South
- Surface > Troposphere
- Acceleration of trend

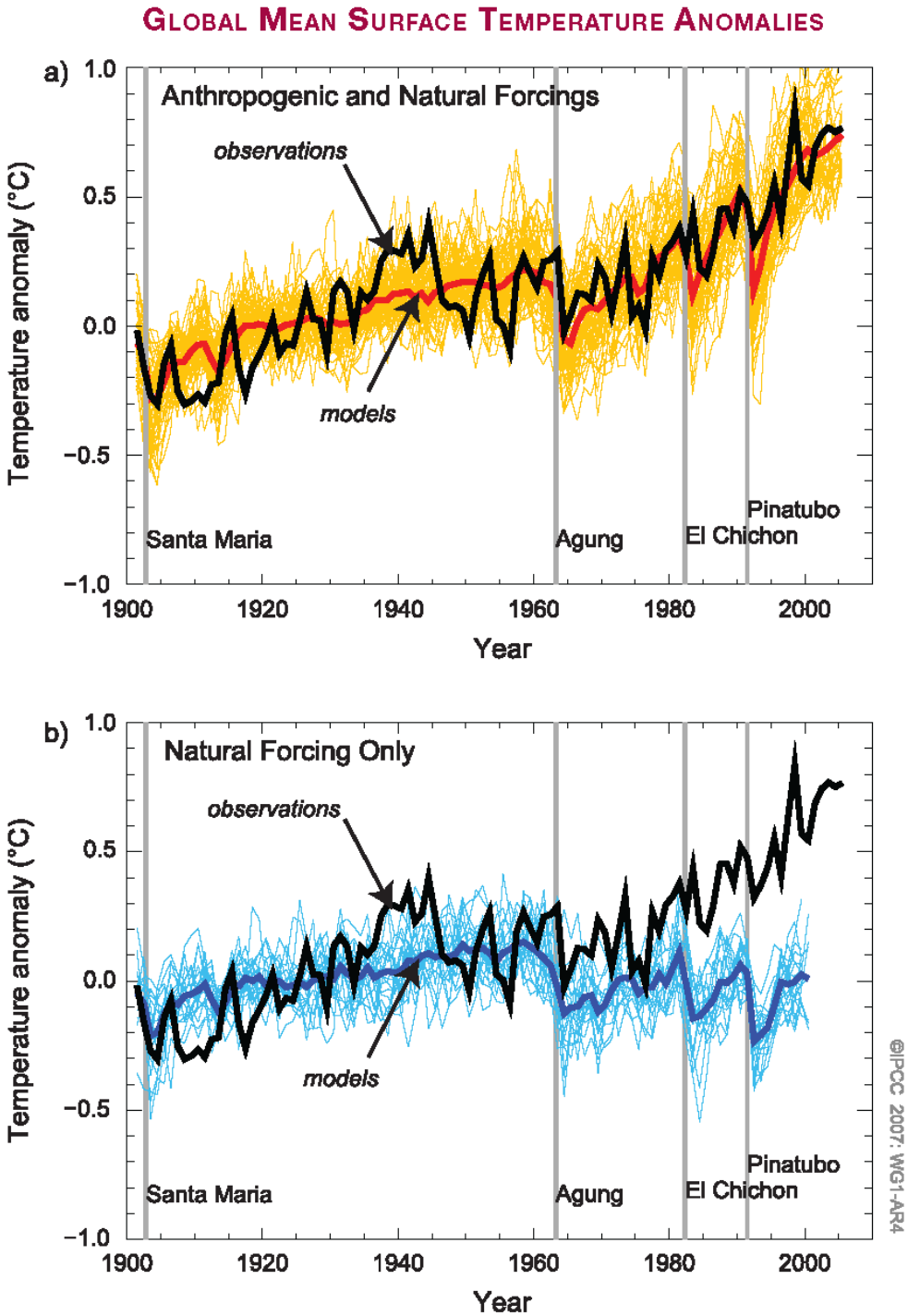


140 Years of Data

Paleo-temperature

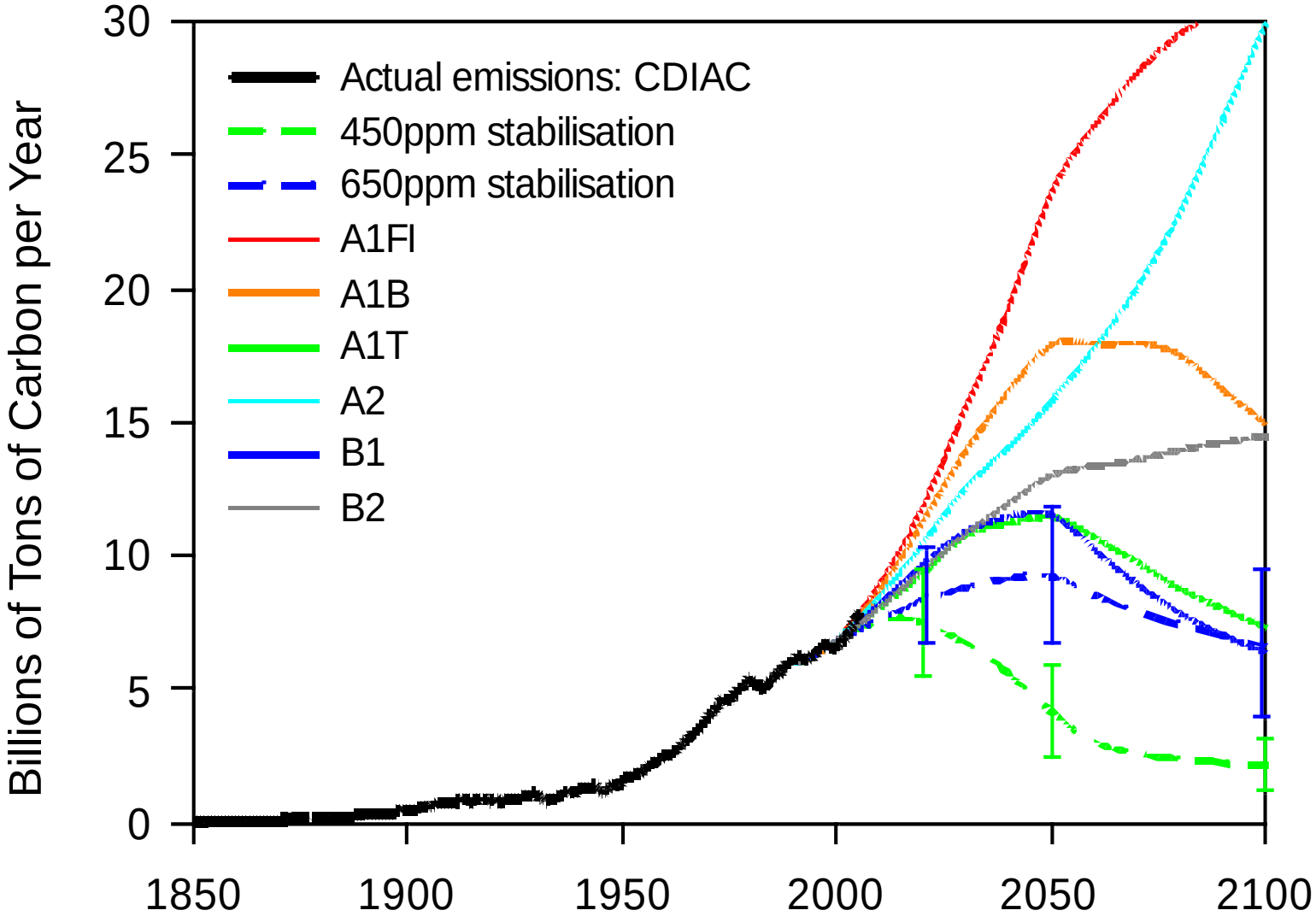


20th-Century Temperatures



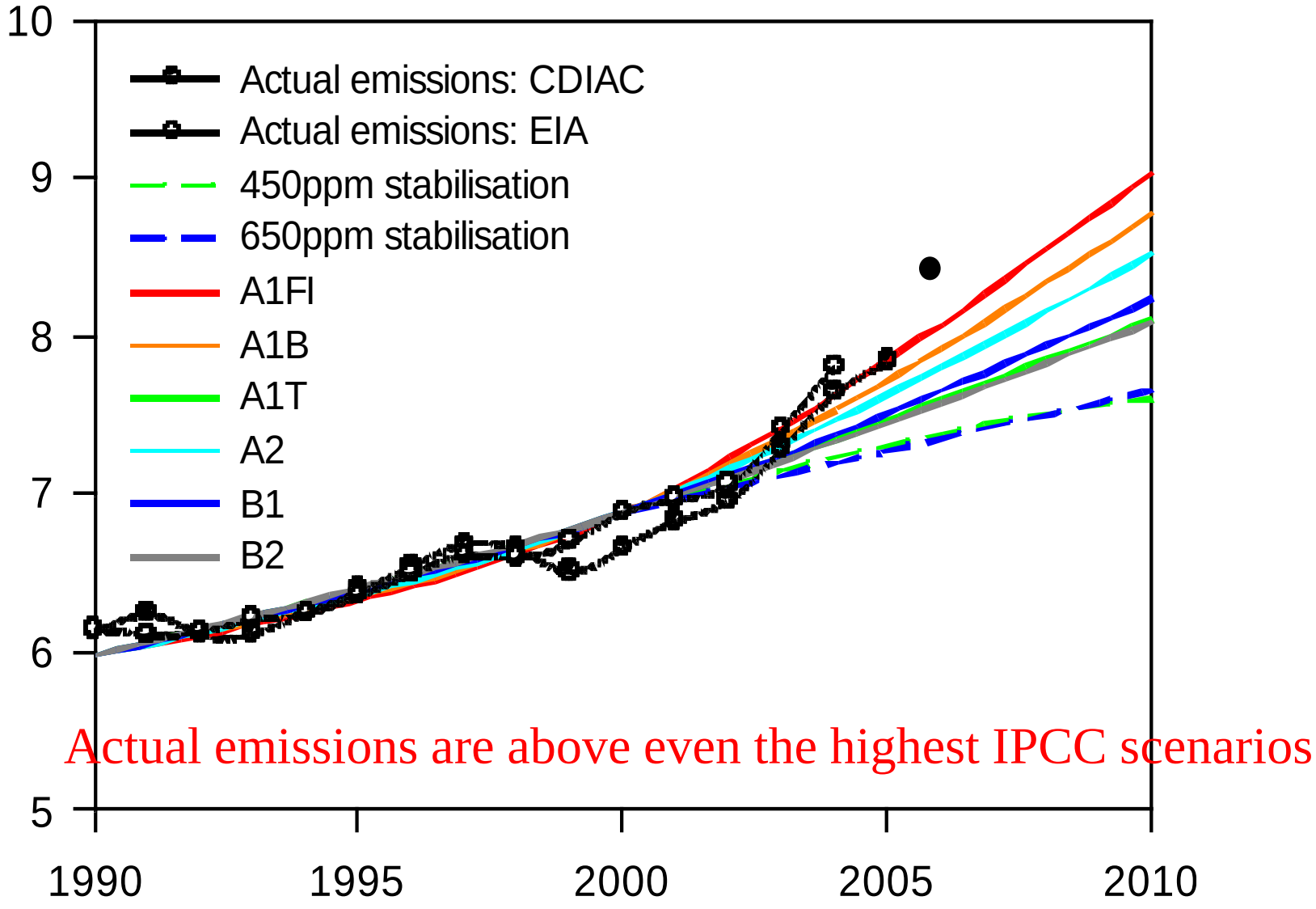
- Black lines show obs, yello lines show each model, red line shows model mean Ts
- With all forcings, models capture much of historical record
- Bottom panels: model

Future Emission "Scenarios"



Economists & Demographers: Different ***self-consistent "stories"*** about population, economic growth,technological development, trade, etc …

Emission Scenarios vs Reality



Raupach et al. 2007 PNAS

Warming in 2090's

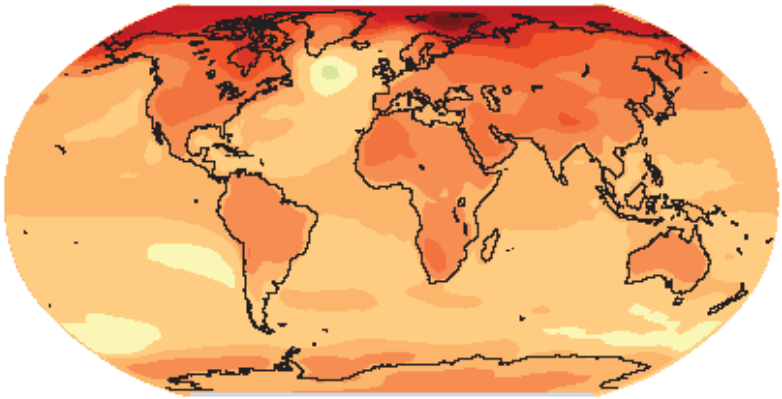
- Land vs ocean!
- North vs South

- Global mean warming of 2° to 5° C
- North American warming of 3° to 6° C

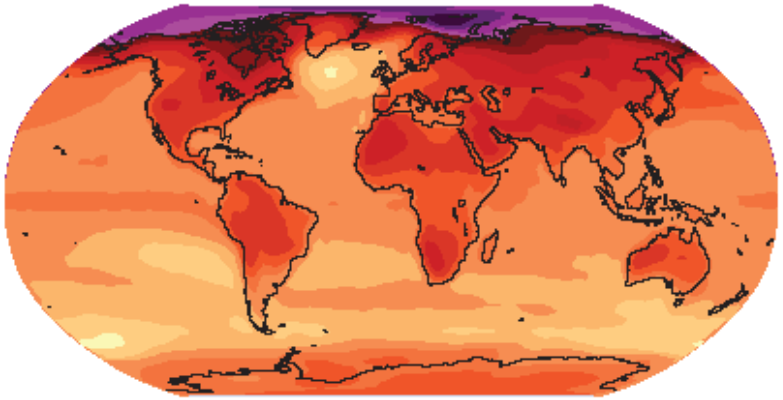
  = 5° to 11° F

- Arctic warming of 8° to 14° F

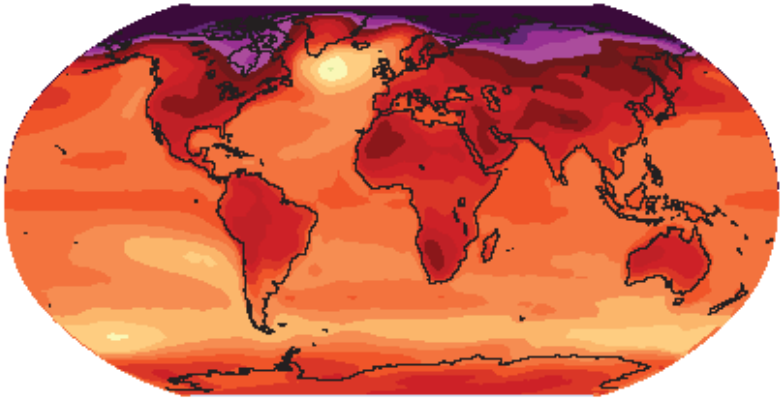
Low Emissions

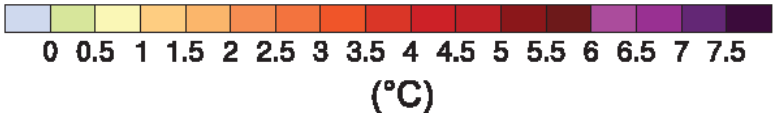


Moderate Emissions



High Emissions



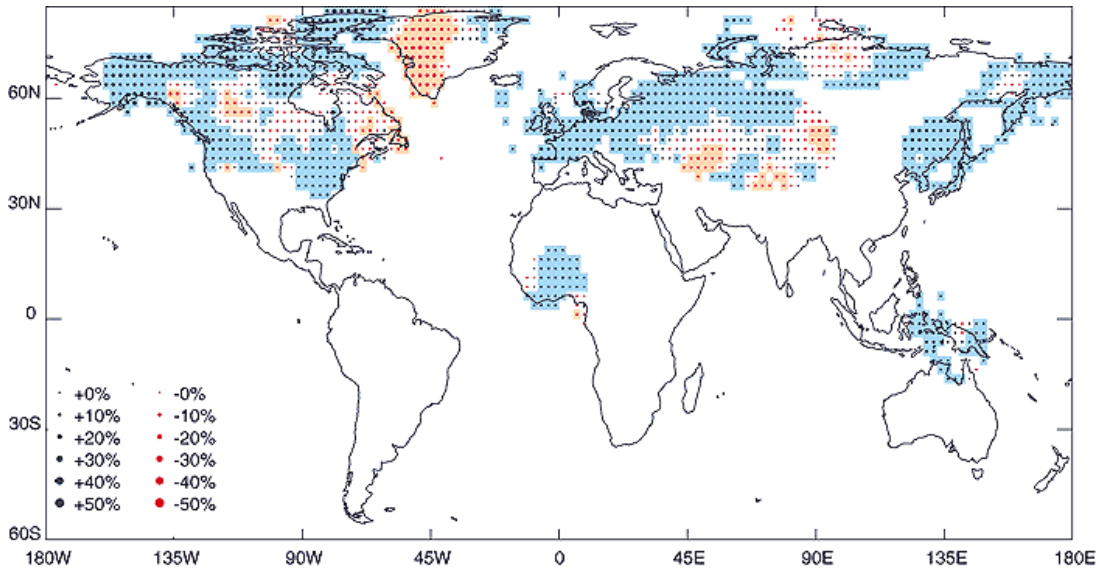


Rainfall? *Agriculture?*

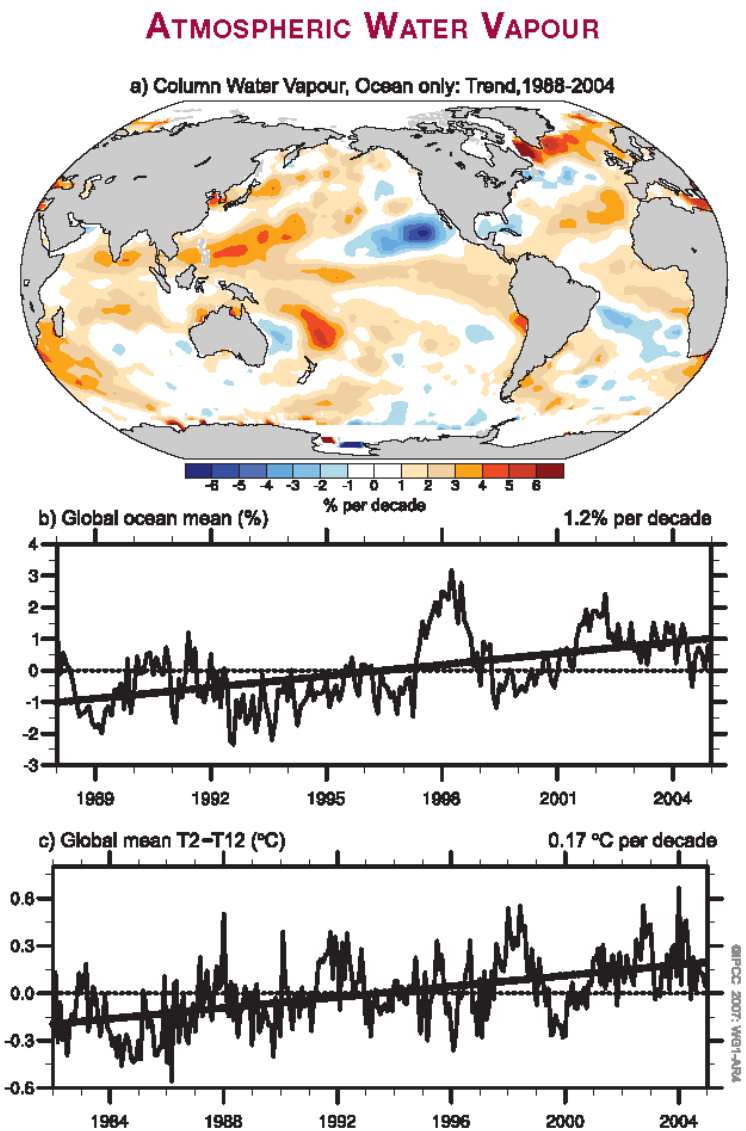
Water supply? *Ski industry?*

Mass immigration?

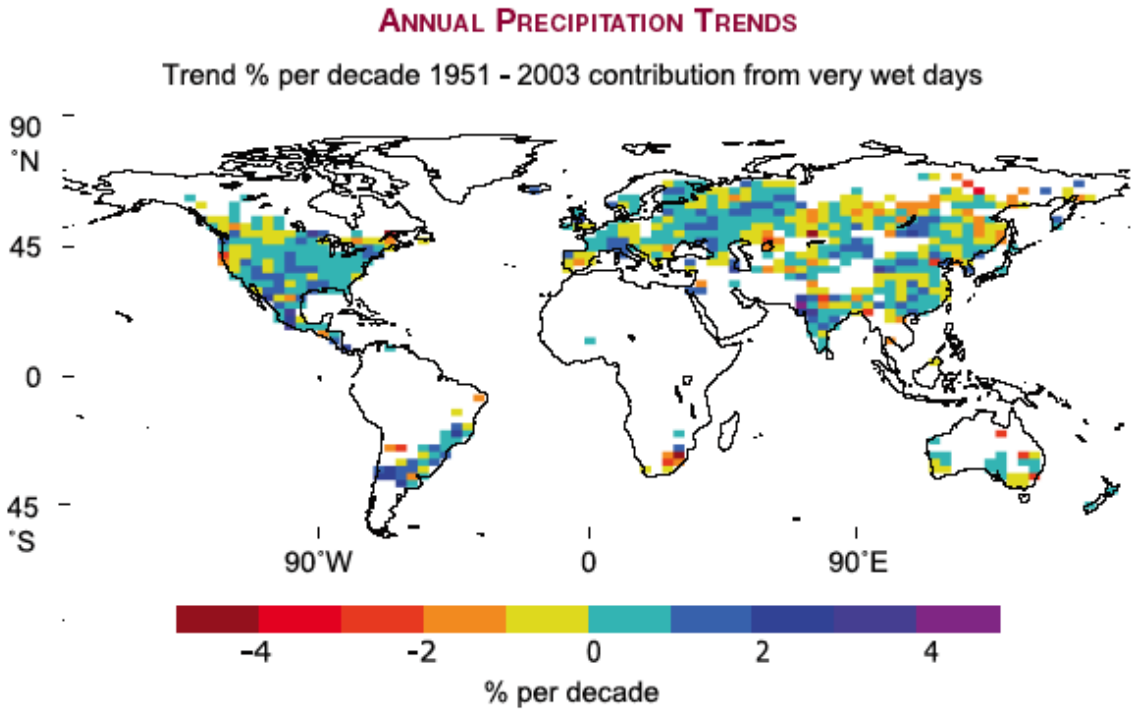
Water Vapor Trends

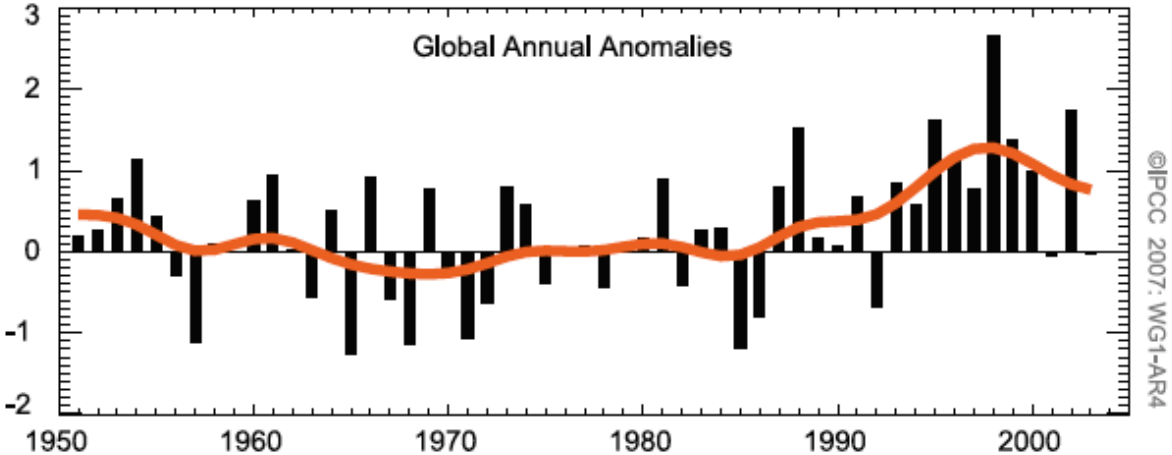


Trends in annual mean surface water vapour pressure, 1975 to 1995, expressed as a percentage of the 1975 to 1995 mean. Areas without dots have no data. Blue shaded areas have nominally significant increasing trends and brown shaded areas have significant decreasing trends, both at the 5% significance level. Biases in these data have been little studied so the level of significance may be overstated. From New et al. (2000).



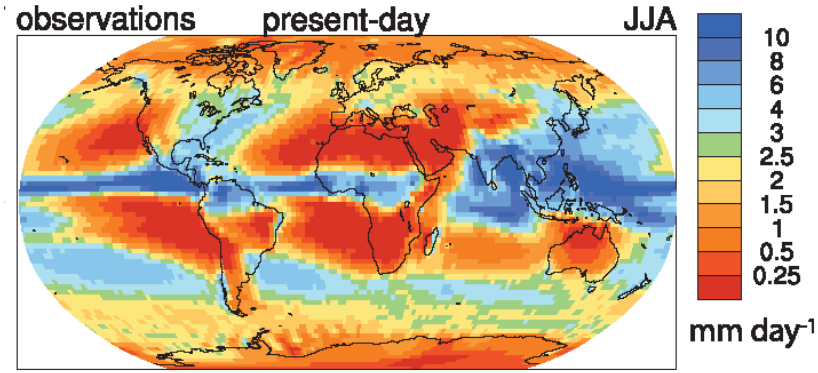
Accelerating Hydrologic Cycle



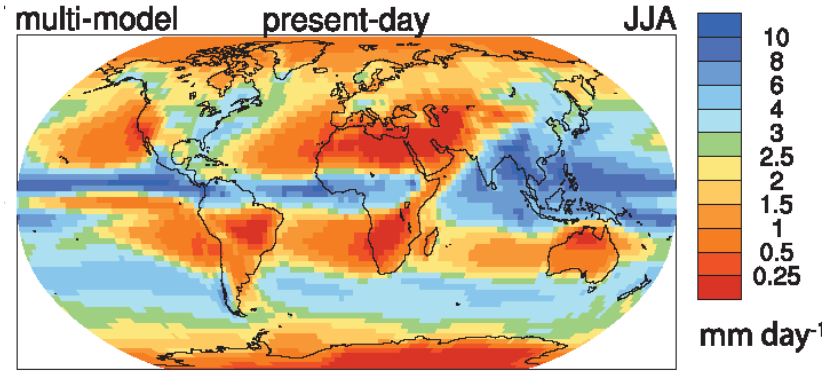


Simulated Precipitation Patterns
(Northern Summer)

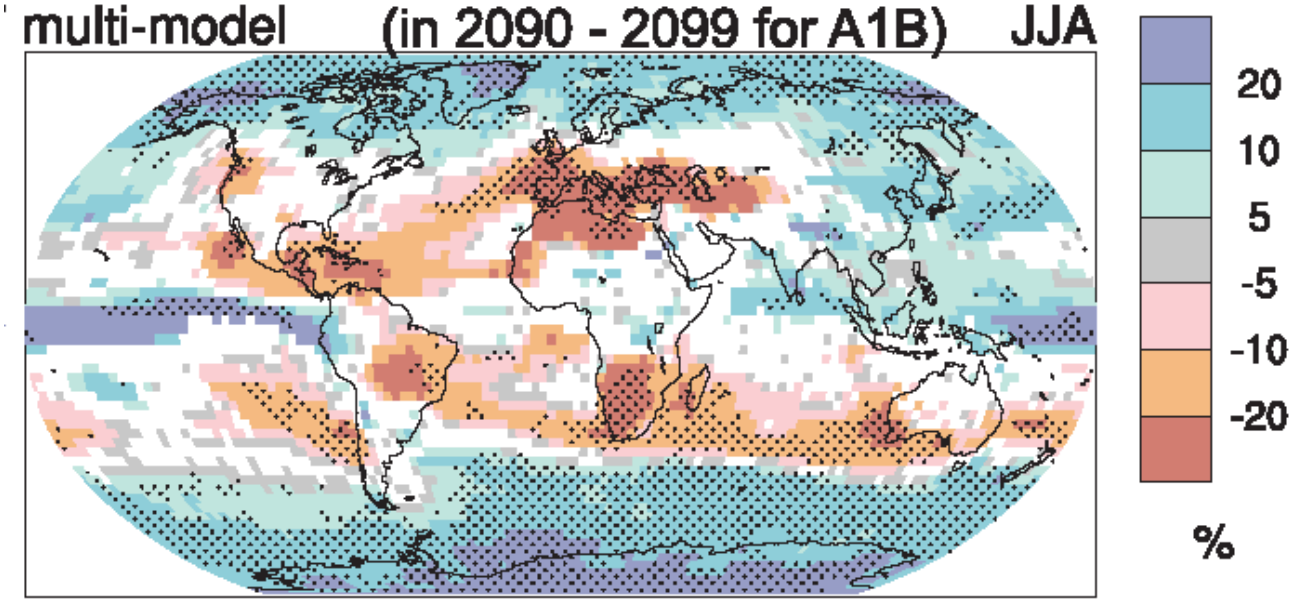
Present Day Observed



Present Day Simulated

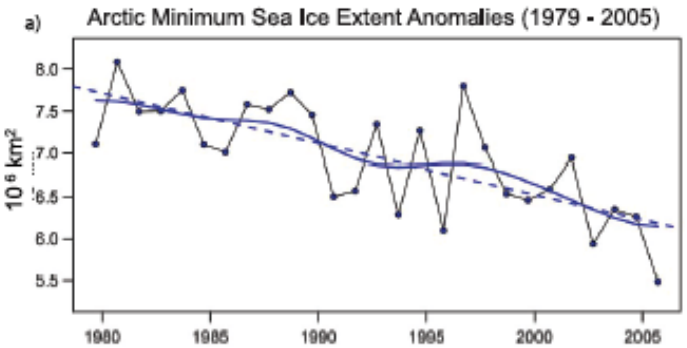


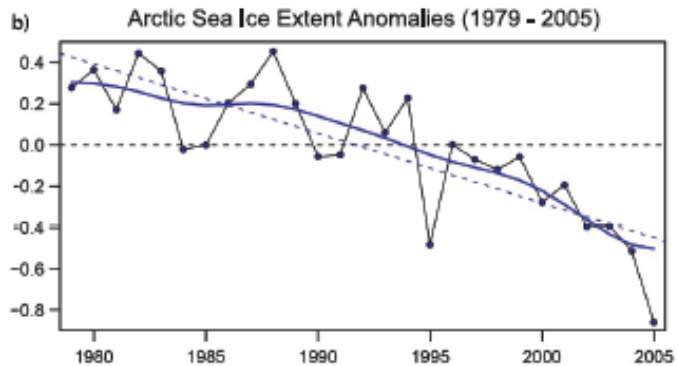
Projected Changes in 2090's

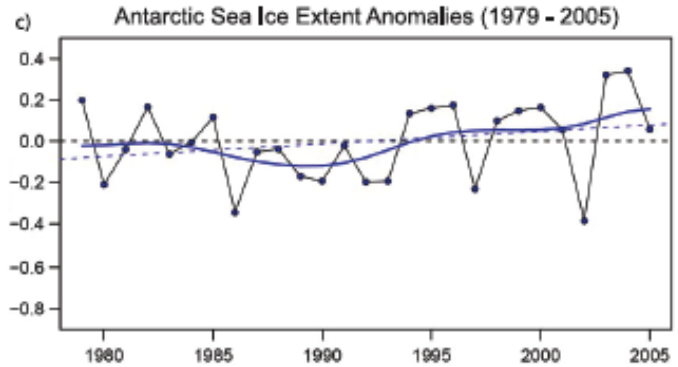


Cryospheric Change

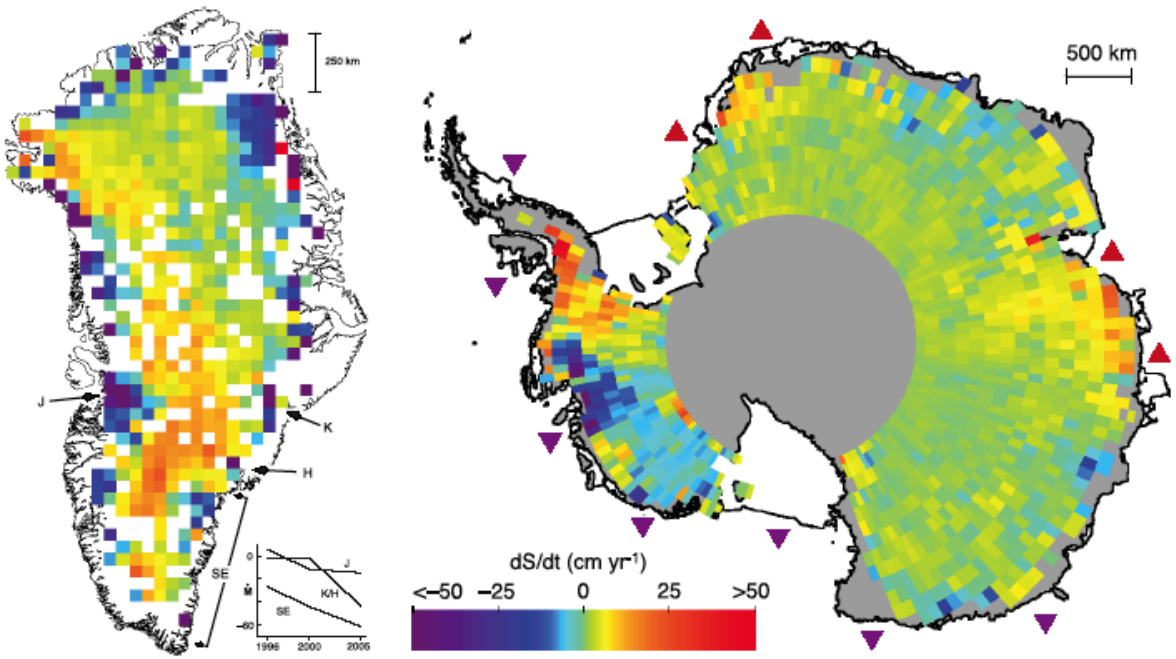
Changes in Sea Ice Extent







Rates of Observed Surface Elevation Change



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Local melting can change both the thickness of ice sheets and the extent of sea ice

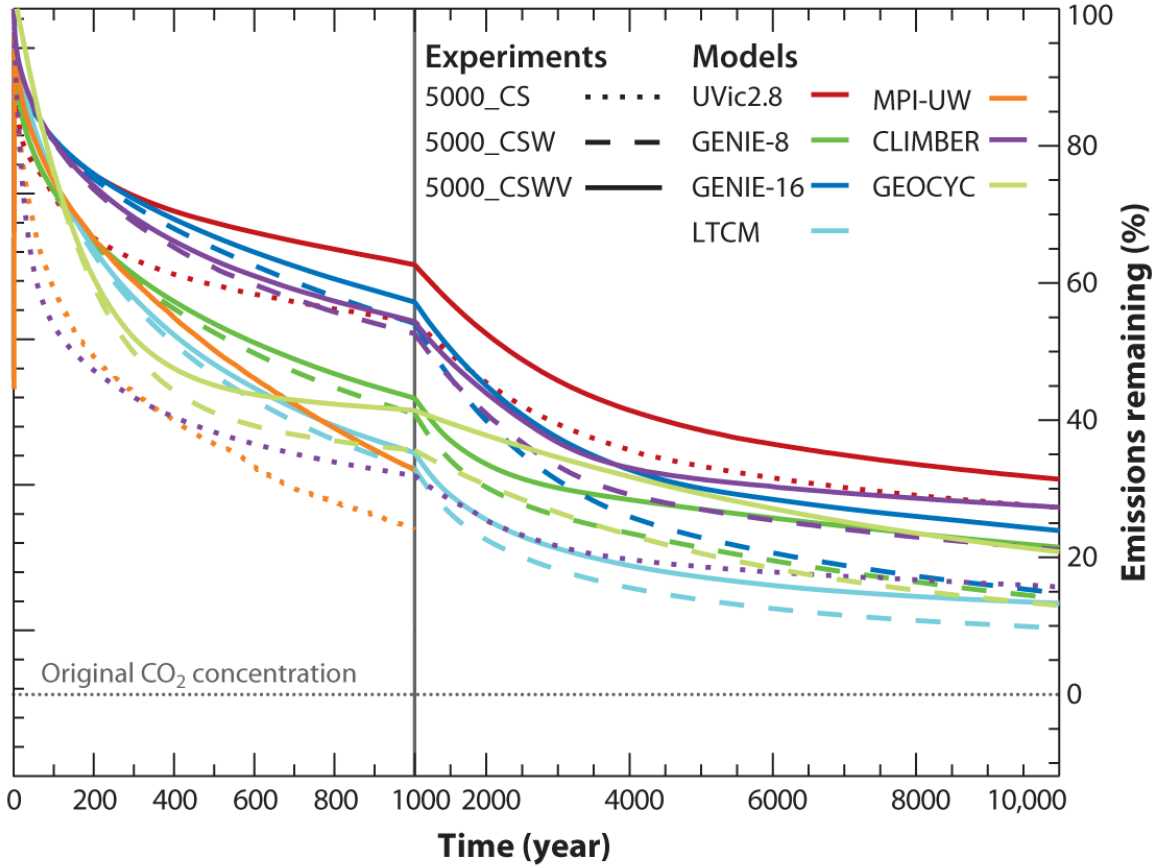
Both sea ice and ice sheets are dynamic (they move in response to a PGF, friction, etc)

Accumulating ice in cold areas due to enhanced precipitation and melting in warmer areas leads to stronger pressure gradients and accelerating ice movement toward coasts

Melting sea ice has no effect on sealevel, but melting land ice does (~7 m for Greenland)

Common Misconception #2

"When we reduce or stop the burning of fossil fuel, the CO_2 will go away and things will go back to normal"



Archer et al, Ann. Rev. Earth Plan. Sci. (2009)

CO_2 from fossil fuel will react with oceans, but only as fast as they "mix"

Eventually, fossil CO_2 will react with rocks

About 1/3 of today's emissions will stay in the air **permanently!**

Historical Perspective

Climate change, CO_2, and energy will probably dominate human affairs for centuries, much as religious wars, feudalism, colonialism, and industrialization before