Climate Forcing, Sensitivity and Feedback Processes

Course Outline

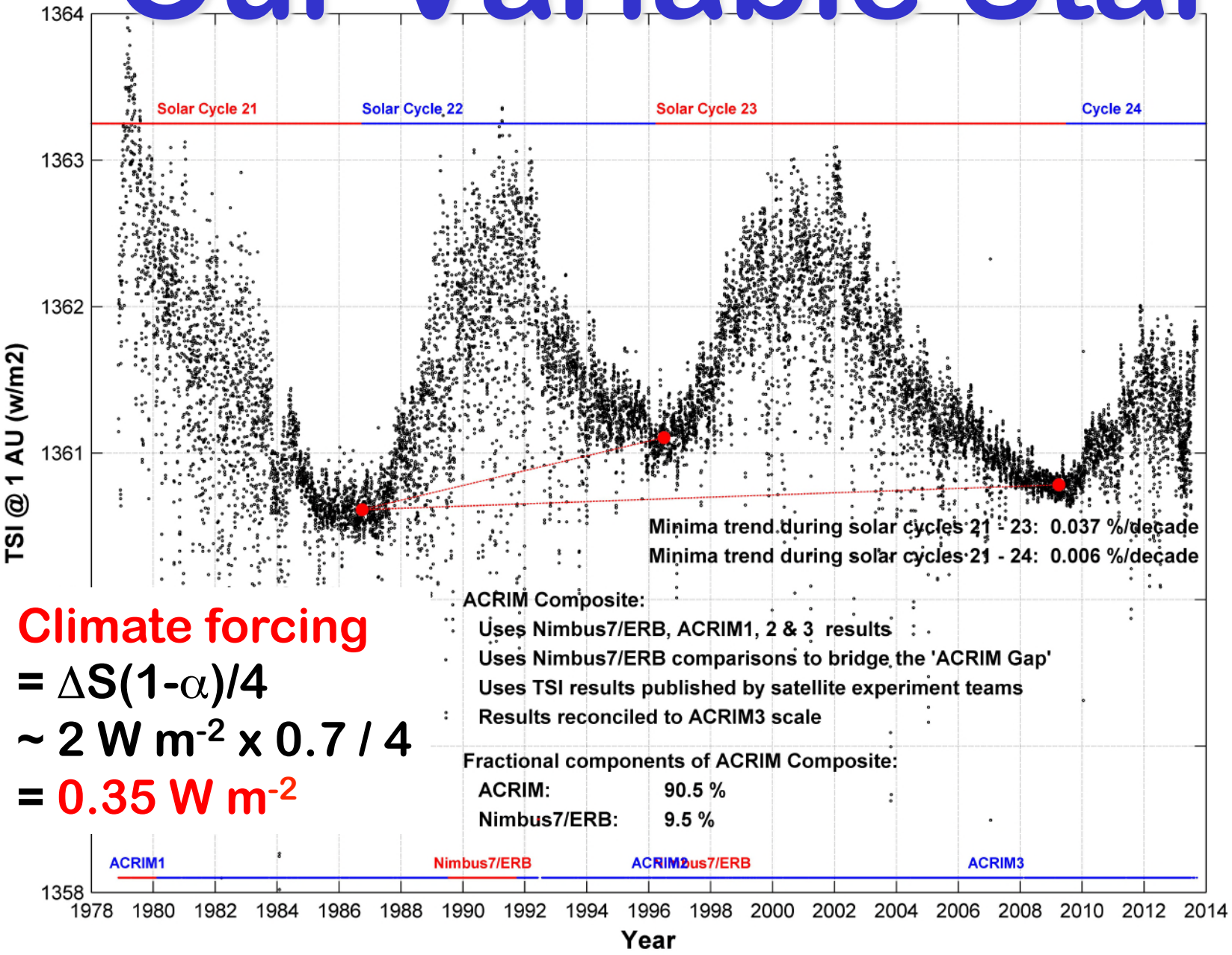
Climate 201: Modern Climate Change

- 2/4 Climate Change in a Nutshell
- 2/11 Forcing, Feedback, & Sensitivity
- 2/18 What to Expect in the Future
- 2/25 Impacts of Climate Change
- 3/4 Mitigation, Adaptation, & Costs

Radiative Forcing

How CO_2 Warms the Climate

Our Variable Star



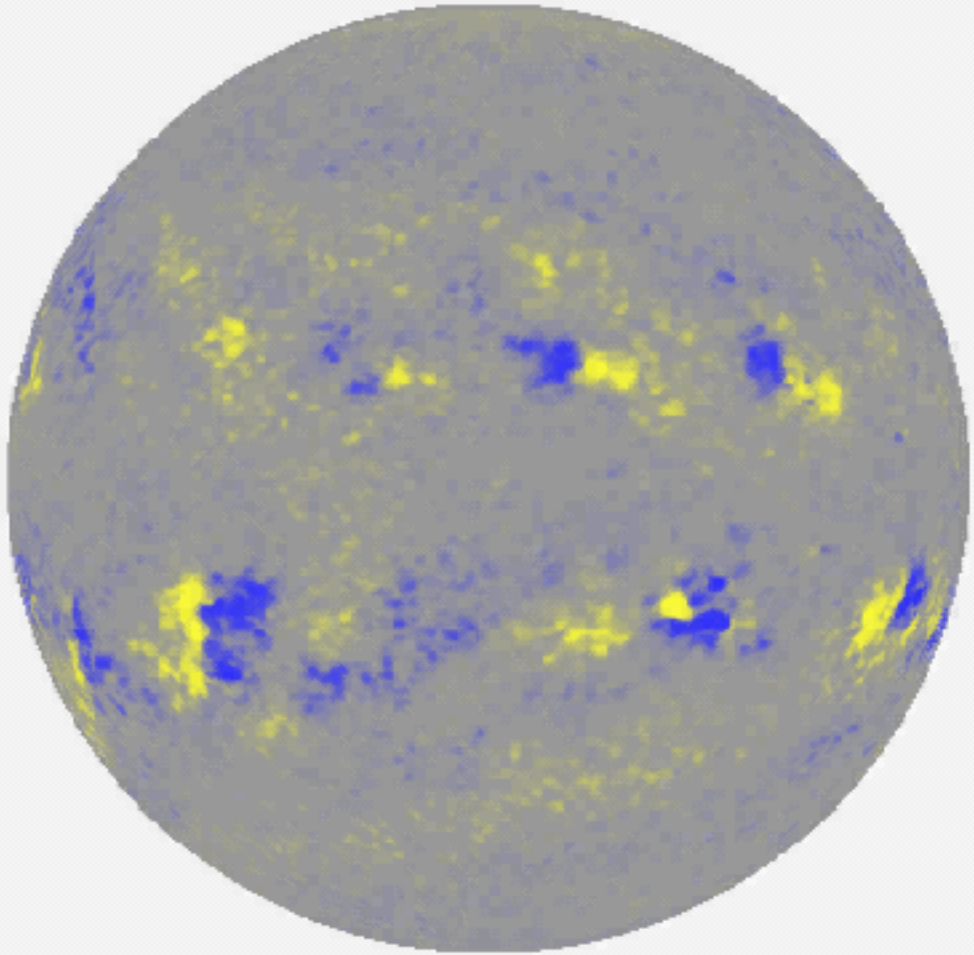
Climate forcing

$\equiv \Delta S(1-\alpha)/4$

$\sim 2\ W\ m^{-2} \times 0.7 / 4$

$\equiv 0.35\ W\ m^{-2}$

Cycle of Solar Variability



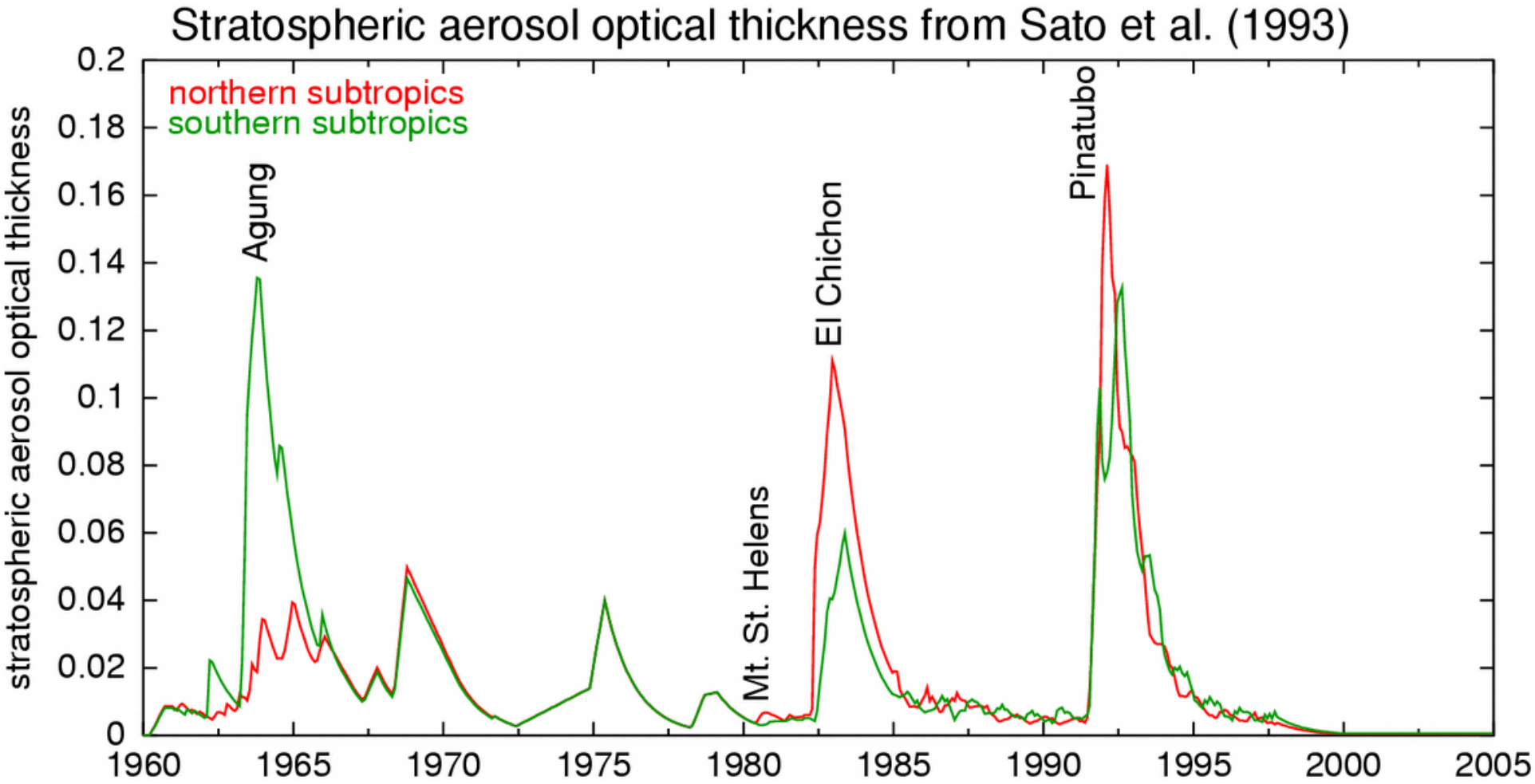
11-year magnetic cycle

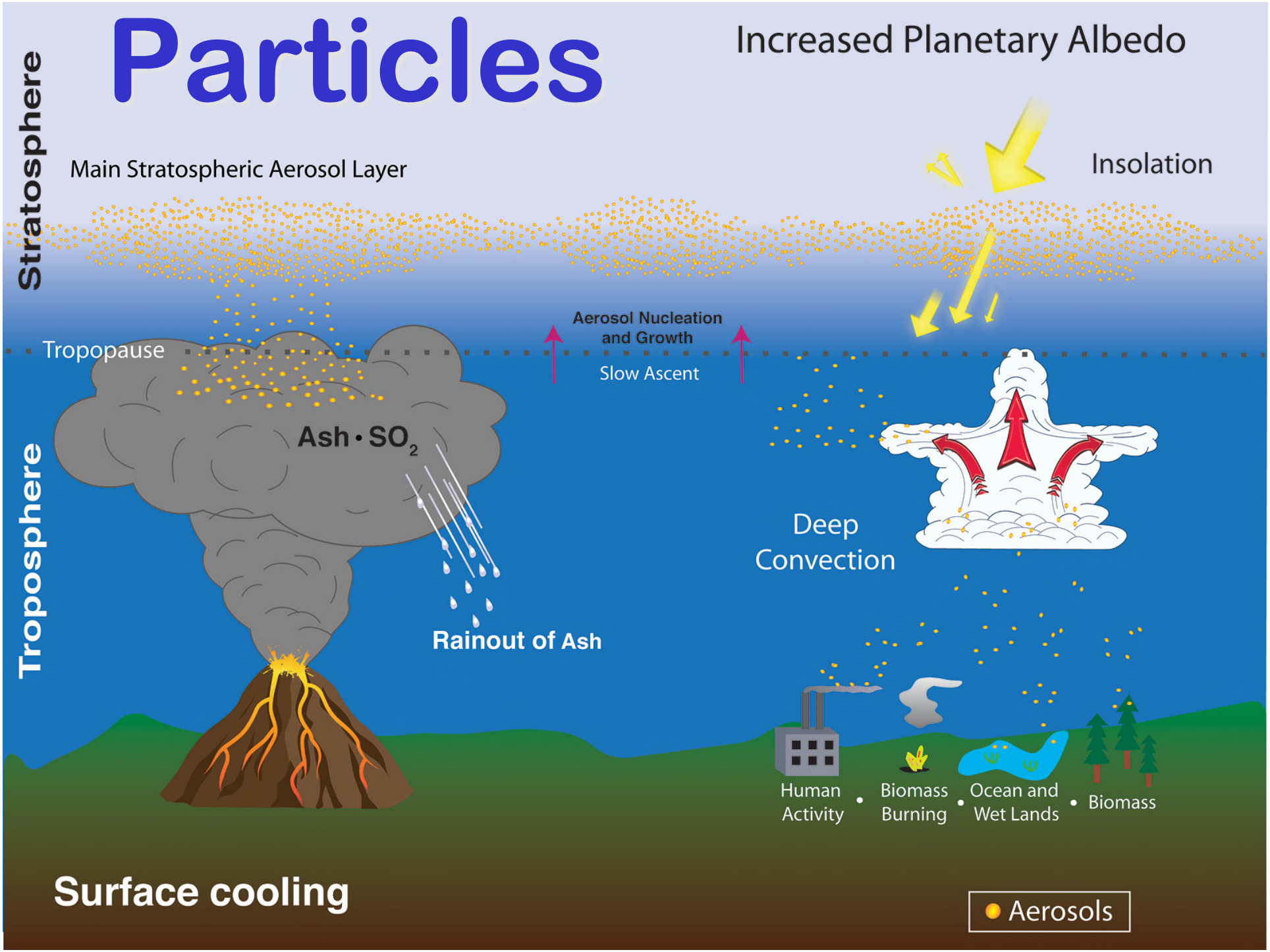
active sun 0.15% brighter

BOOM!

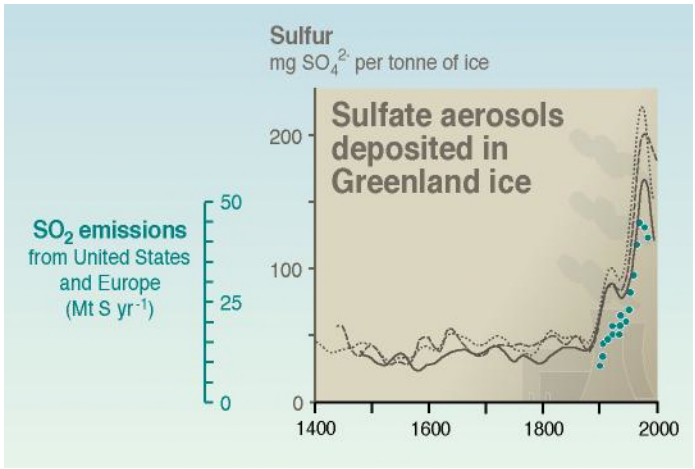
- Volcanoes release huge amounts of SO_2 gas and heat
- SO_2 oxidizes to SO_4 particles ("aerosol") and penetrates to stratosphere
- SO_4 aerosol scatters solar radiation back to space

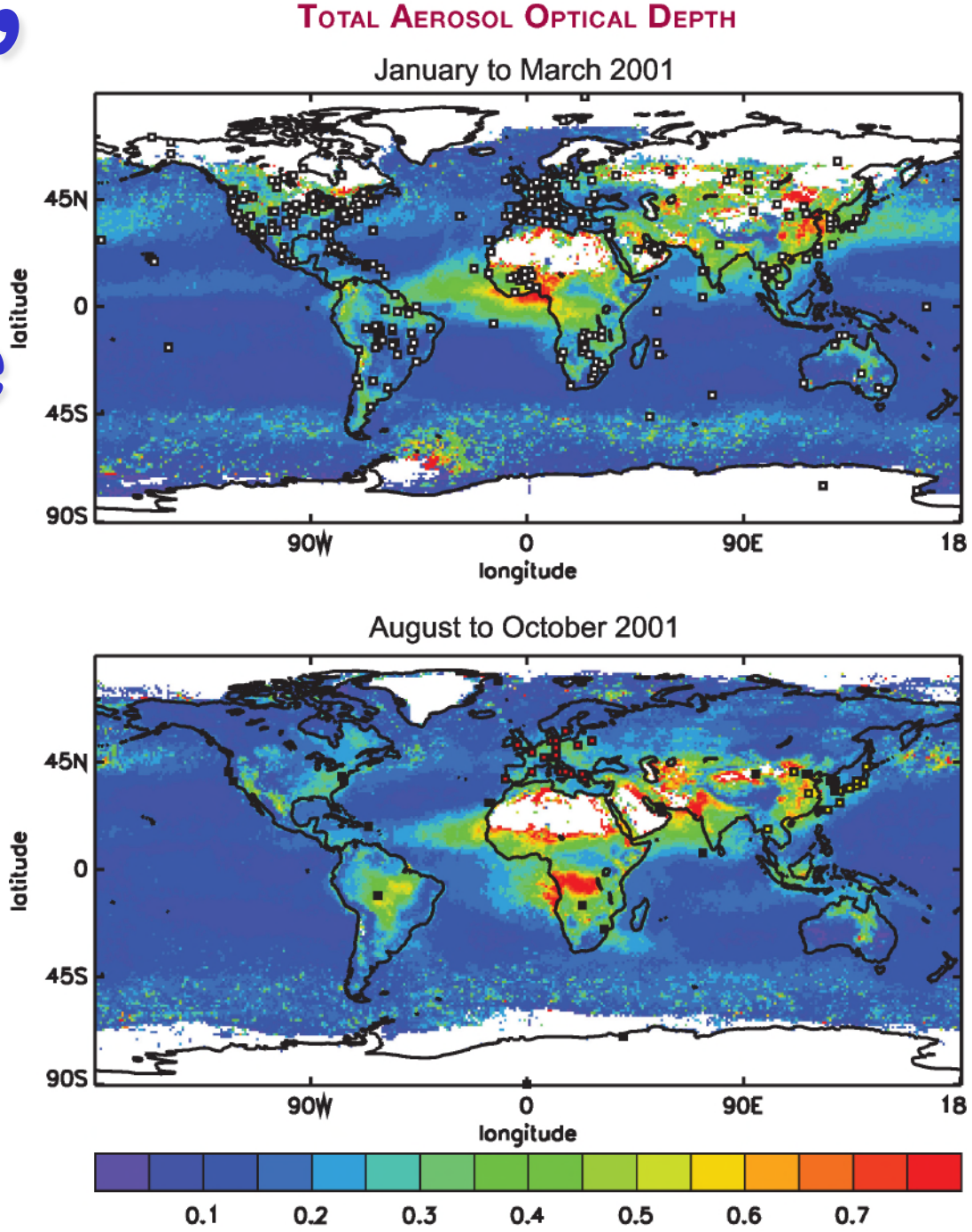
Volcanic Aerosol




Particles
Increased Planetary Albedo
Stratosphere
Main Stratospheric Aerosol Layer
Insolation
Aerosol Nucleation
and Growth
Slow Ascent
Tropopause
Troposphere
Ash • SO2
Rainout of Ash
Deep
Convection
Human
Activity
Biomass
Burning
Ocean and
Wet Lands
Biomass
Surface cooling
Aerosols

"Aerosol" Particles in Troposphere from air pollution





Tropospheric Aerosol
Enhance Cloud Albedo

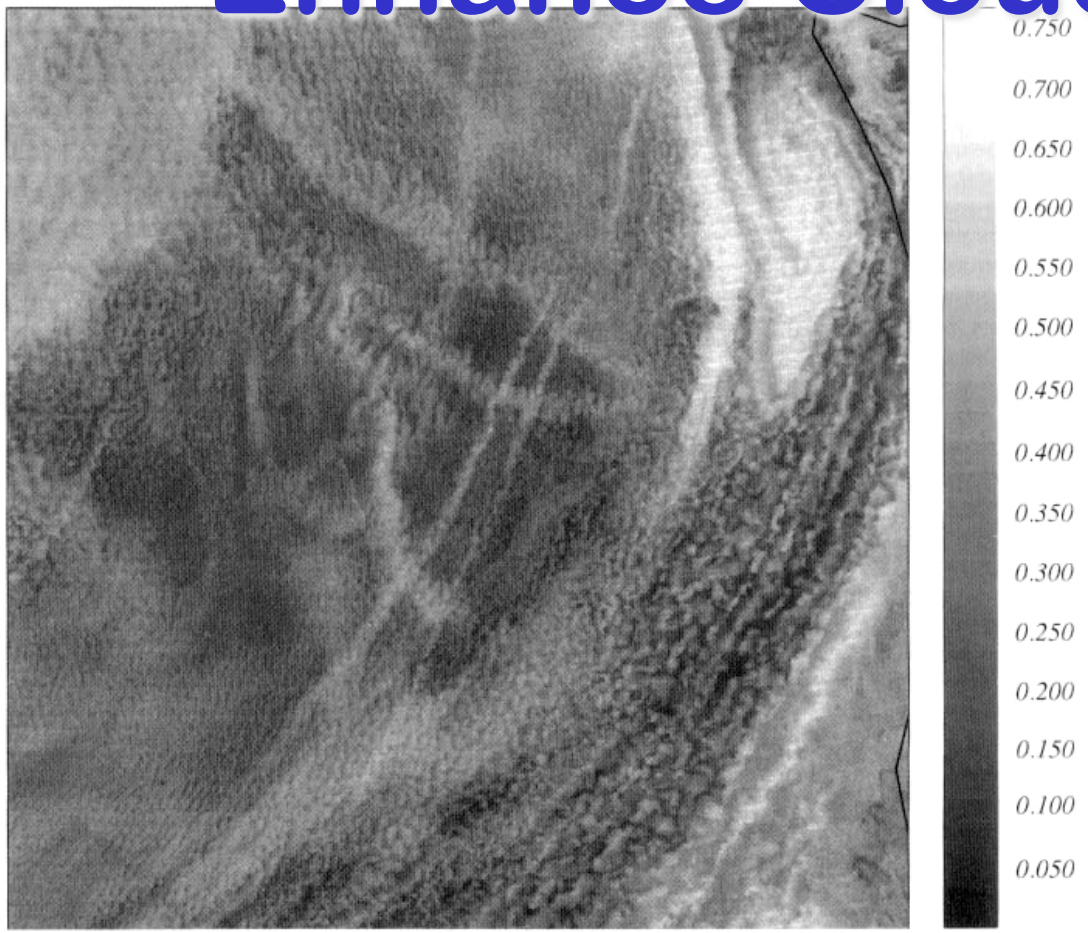
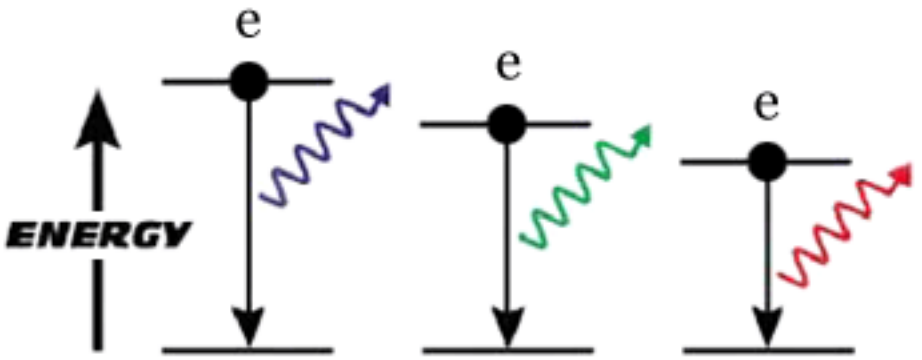
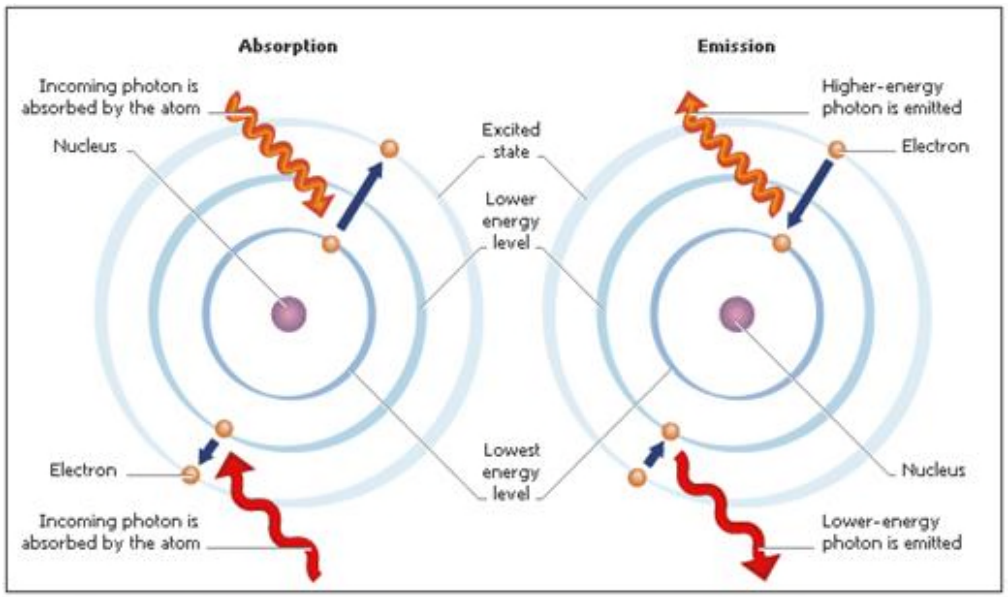


Fig. 12.6 GOES 1-km visible image of stratocumulus clouds over the Pacific Ocean on July 1, 1987 at 1615 UTC (Universal Time Coordinate). The scale of the image is approximately 5° square. The continental outline in the upper right is the Olympic Peninsula of Washington, and the one in the lower right is Cape Blanco on the Oregon coast. The linear features in the center of the image are ship tracks, enhancements of otherwise thin stratocumulus clouds caused by sulfur gas and particulate emissions of passing ships. The gray scale on the right indicates the visible albedo. (Image courtesy of Robert Pincus.)

- Ship tracks off west coast
- Cloud droplets condense on tiny particles
- Makes more/ smaller cloud drops
- Clouds are brighter (higher albedo)

Atomic Emission

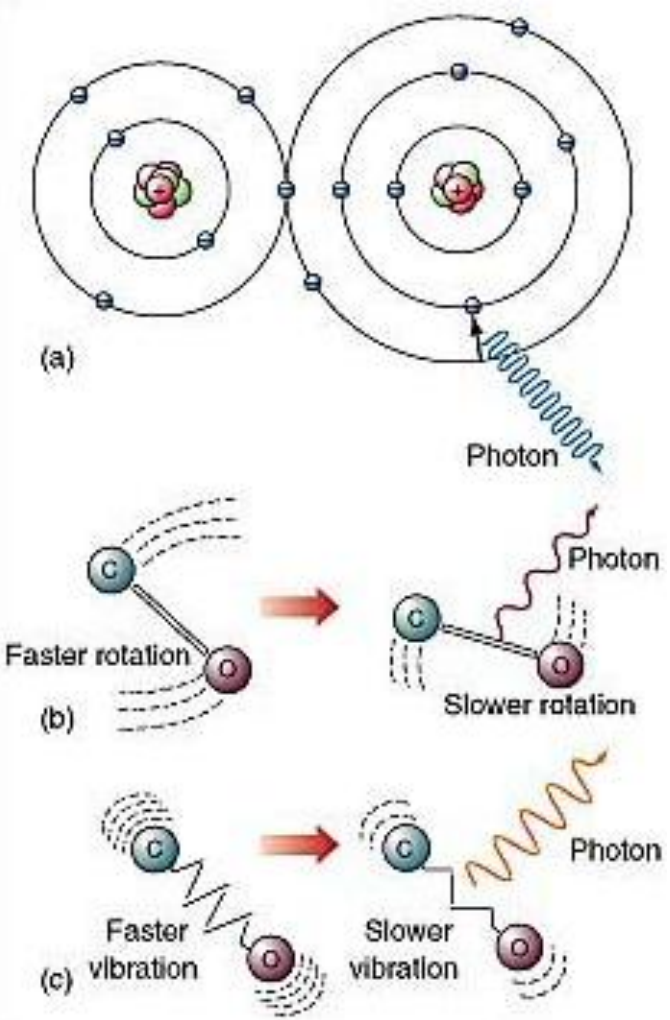




- Big jumps take lots of energy, small jumps take less
- Big drops emit energetic photons (short wavelengths)
- Small drops emit less energetic photons (longer wavelengths)

Most electron transitions in gases absorb/emit visible or UV light

Molecules and Photons

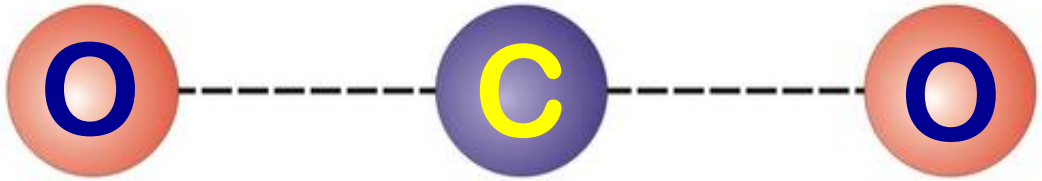


- Molecules are groups of atoms that share electrons (chemical bonds)
- Molecular transitions involve changes in vibration, rotation, bending, and stretching of chemical bonds
- Photons can interact with molecules to change states
- Transitions involve specific amounts of energy, so only certain wavelengths are active

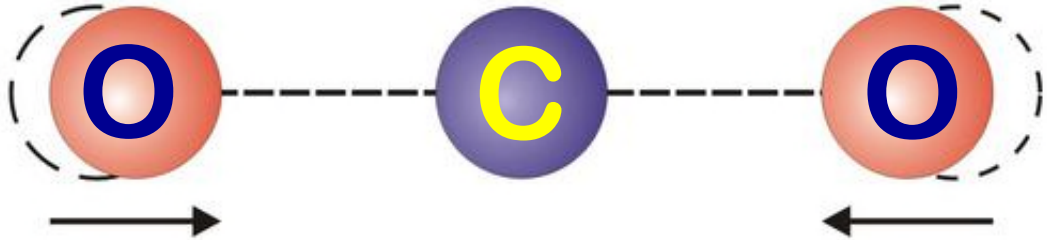
Molecular transitions typically absorb & emit in thermal infrared

CO_2 Vibrations

Resting or ground state



No dipole … weak!



7.2 μm

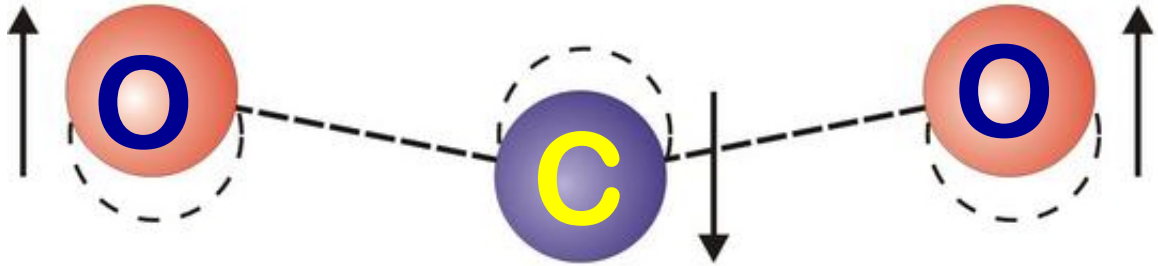
ν_1=1388 cm^{-1}

symmetric stretch

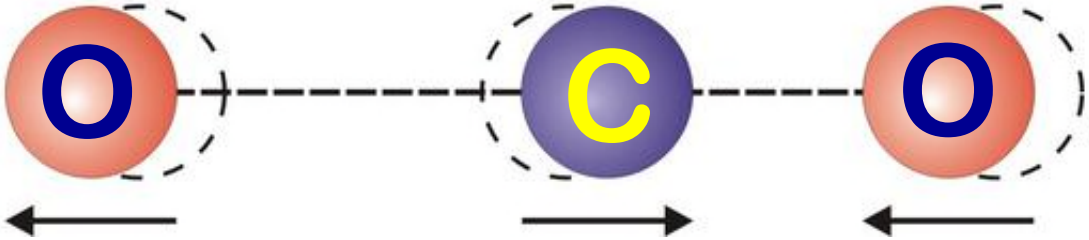
15 μm

ν_2=667 cm^{-1}

bending



Temporary electric dipole … strong!

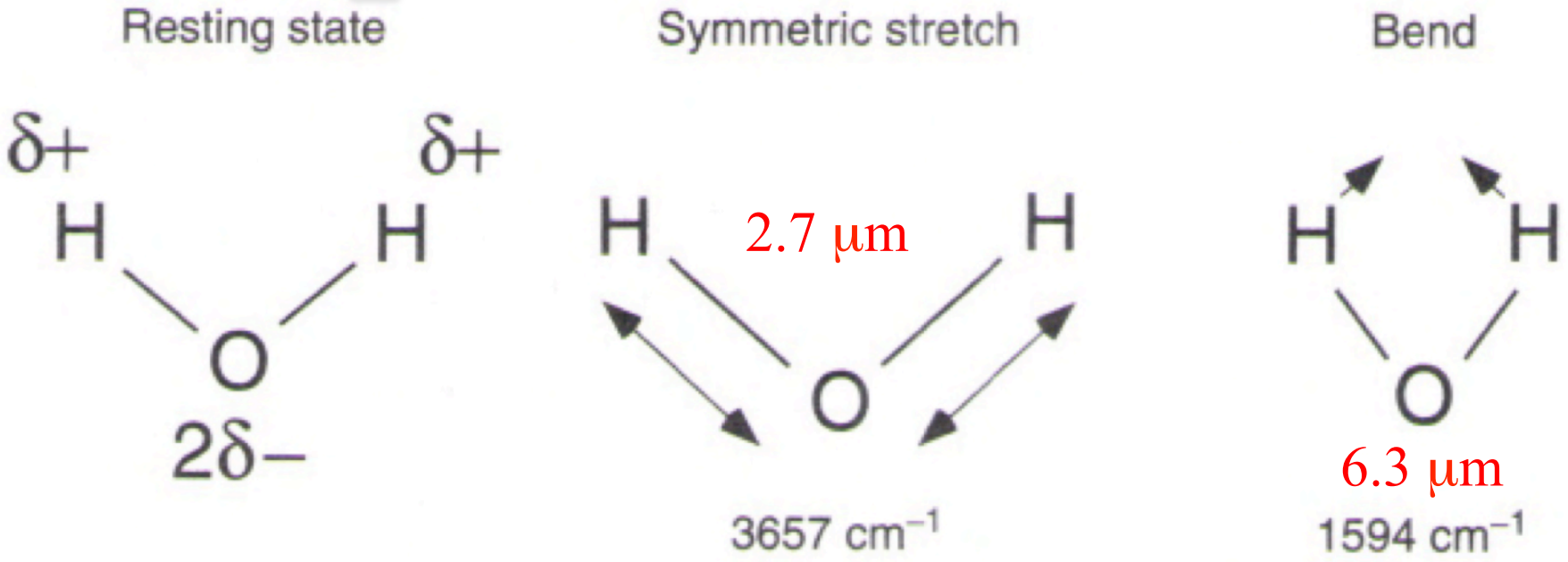


4.3 μm

ν_3=2349 cm^{-1}

asymmetric stretch

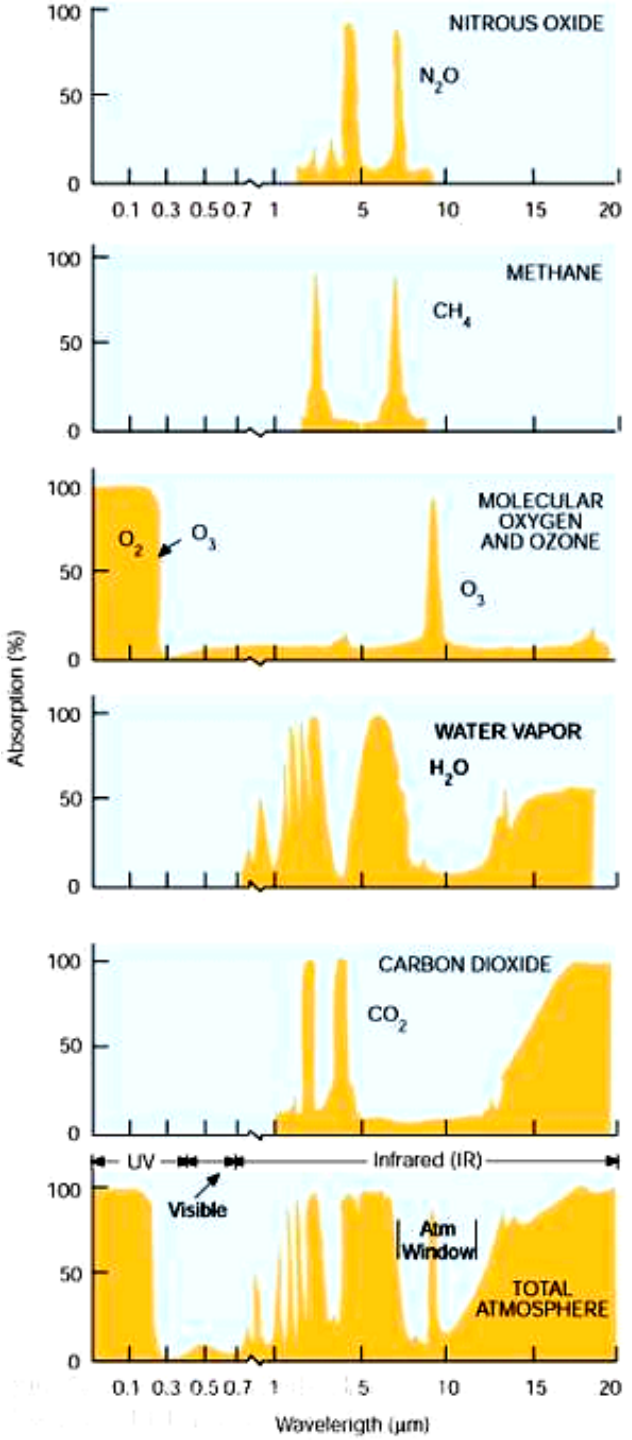
H_2O Vibrations



- **Water molecules are "bent!"**
- **This gives them a positively charged end (with the hydrogen) and a negatively charged end (with the oxygen)**
- **This "permanent dipole moment" allows H_2O to absorb & emit photons without moving bonds**

Atmospheric Absorption

- Visible radiation passes almost freely through Earth's atmosphere
- Earth's emitted thermal energy either fits through a narrow "window" or is absorbed by greenhouse gases and reradiated
- Complete absorption from 5-8 μm (H_2O) and > 14 μm (CO_2)
- Little absorption between about 8 m and 11 μm ("window")



Optical "Thickness"

14.3 μm CO_2 band

11 μm "window"

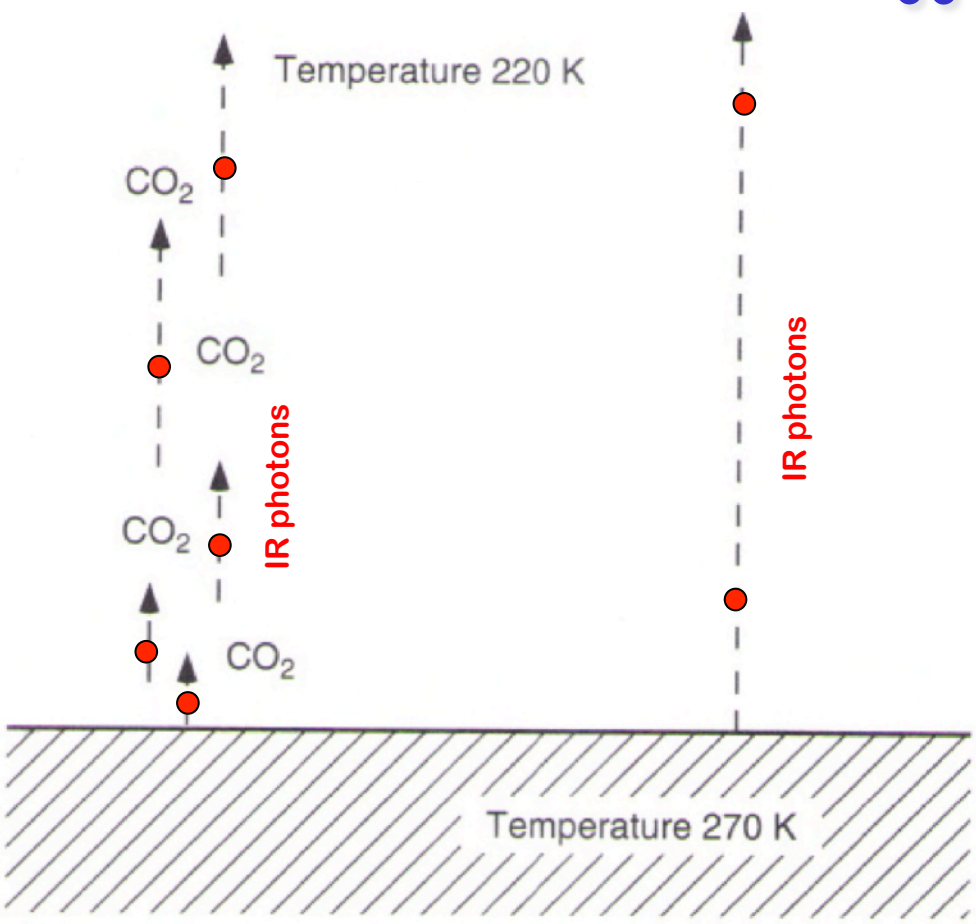
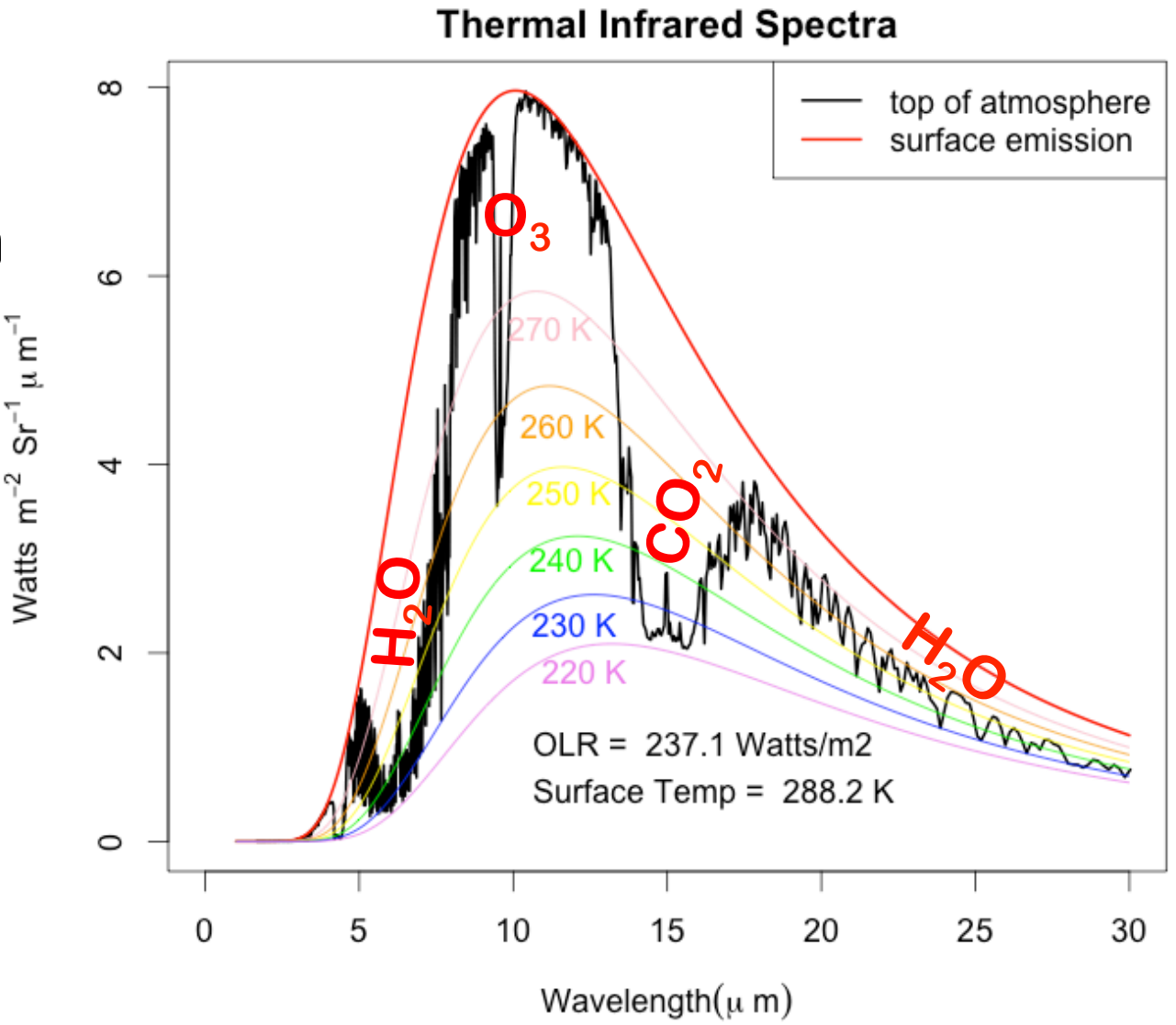


Figure 4-4 A comparison of the fate of infrared light in the optically thick CO_2 bend frequency (*left*) versus the optically thin atmospheric window (*right*).

- In CO_2 absorption bands, atmosphere is totally opaque to IR photons
- They get absorbed and re-emitted higher up
- It's cold up there!
- Think about the Layer Model

View from Space

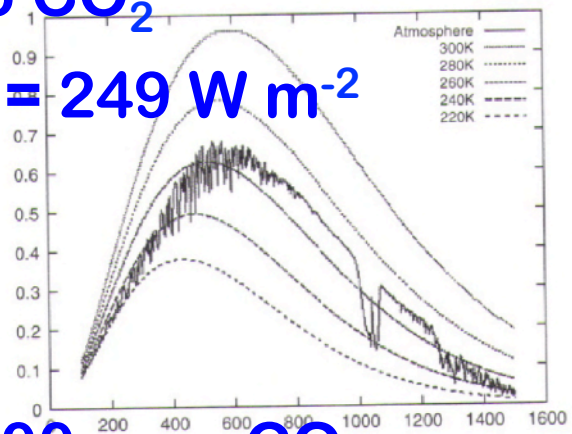
- Hot surface emits directly to space in window region
- Cold upper layers emit to space in optically thick regions
- Total emission much less than from sfc



Absorption by CO_2 Causes Warming

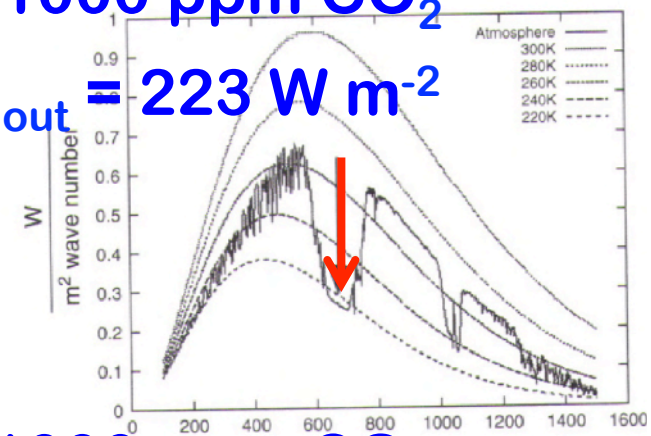
No CO_2

I_{out} = 249 W m^{-2}



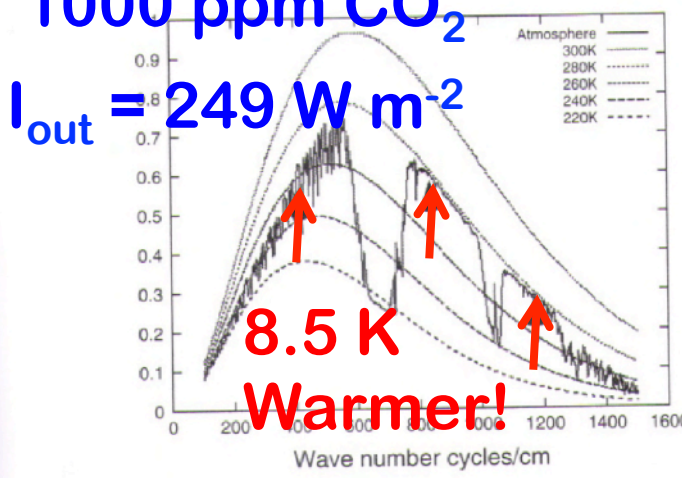
1000 ppm CO_2

I_{out} = 223 W m^{-2}



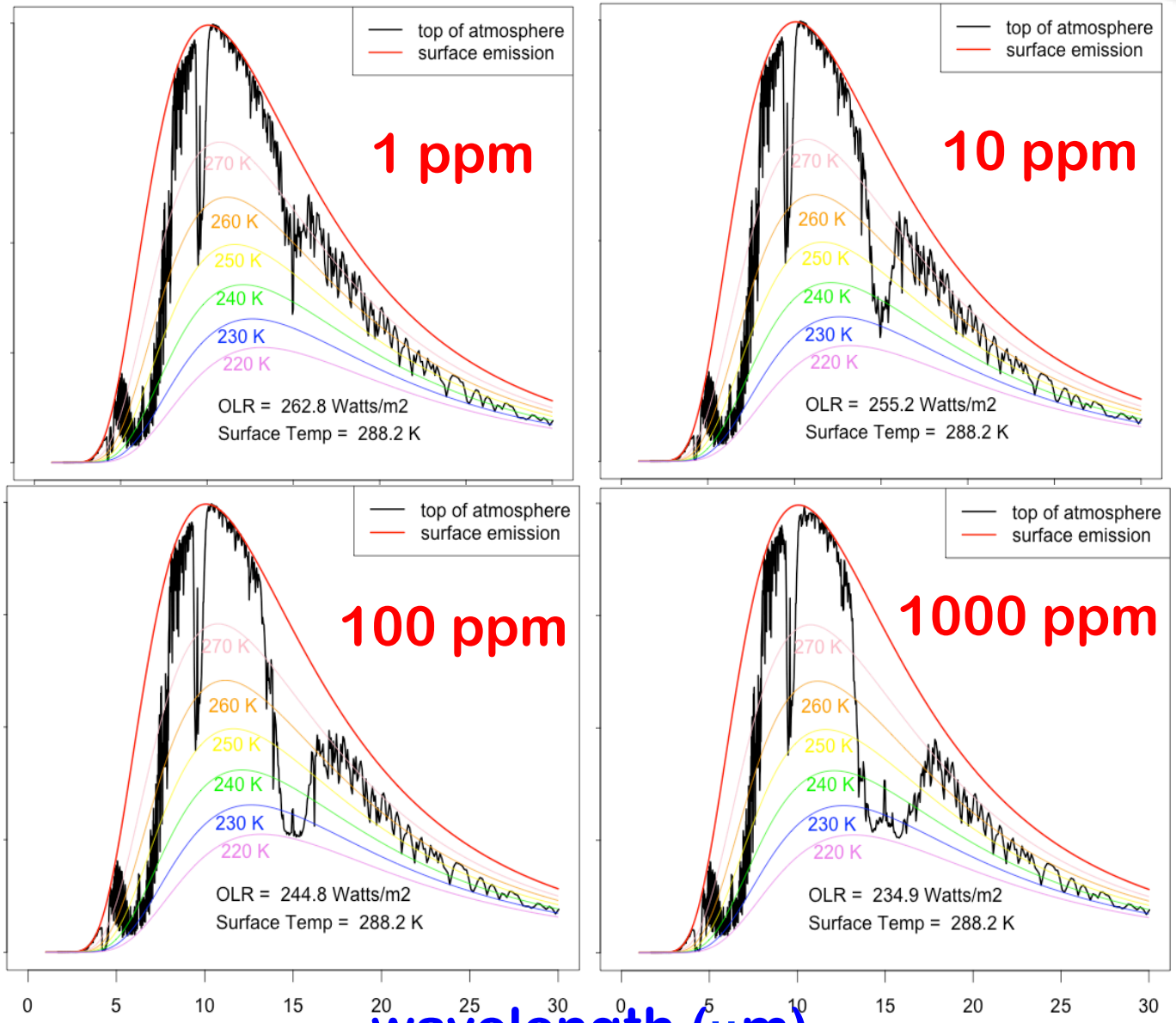
1000 ppm CO_2

I_{out} = 249 W m^{-2}



- As CO_2 is added, big parts of the spectrum are emitted higher up where it's colder
- This reduces the rate of total heat loss below solar gain
- The surface warms to compensate, emitting more from window regions, to re-establish equilibrium w/sun

Effect of Adding CO_2



- Optically thick regions are as cold as they can get
- But the thick regions get wider with added CO_2
- Rate of total emission (area under black curve) decreases less and less

Band Saturation

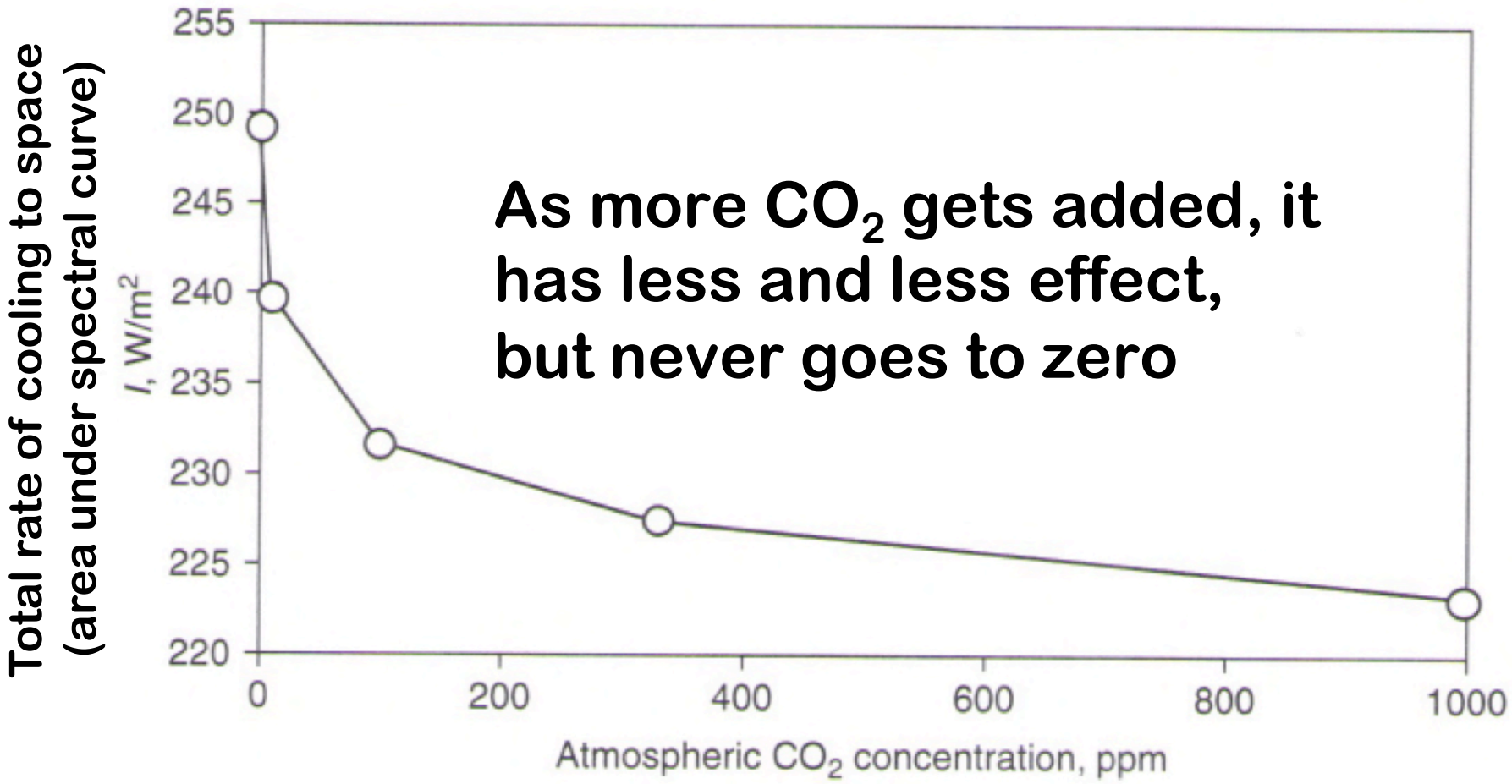
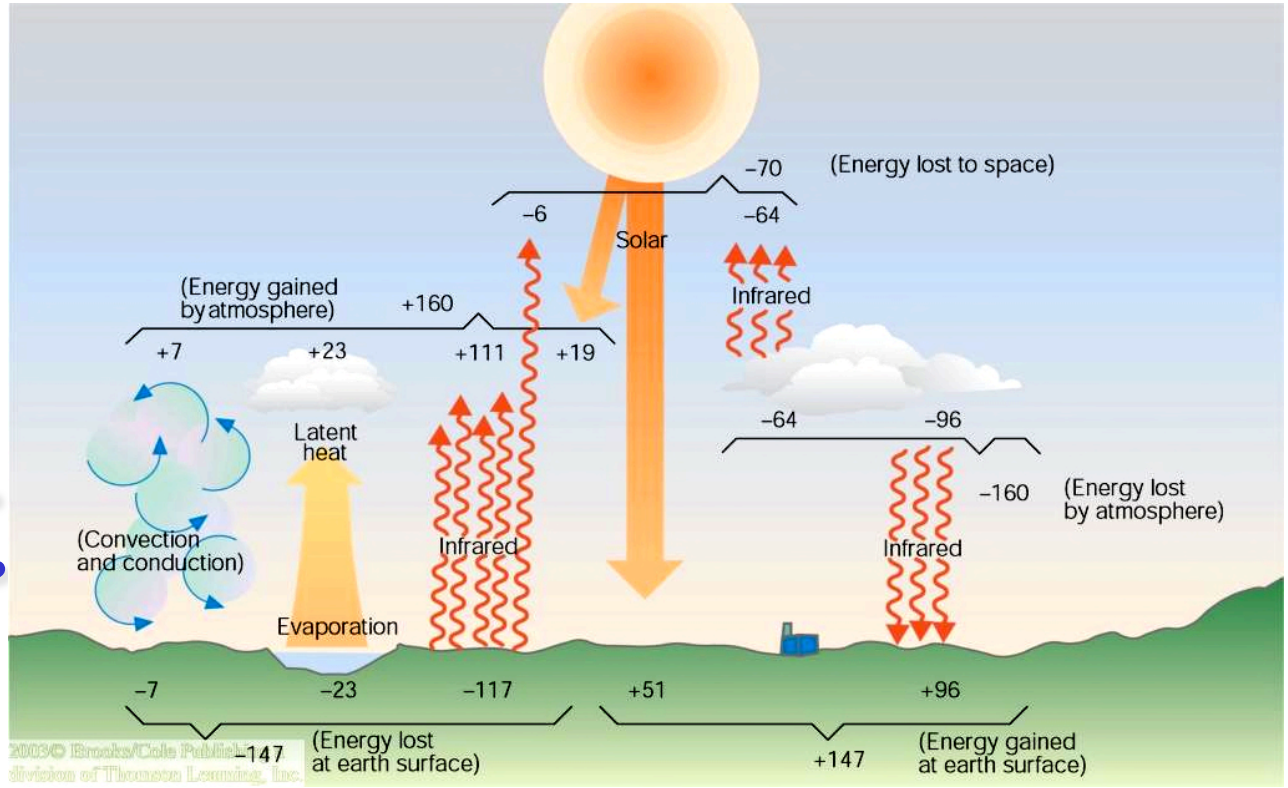


Figure 4-6 Band saturation viewed in a different way from Figure 4-5. This is a plot of the total energy flux carried by all infrared light, which is proportional to the area under the spectrum curves in Figure 4-5. The outgoing energy flux is less sensitive to CO_2 when the CO_2 concentration is high.

Energy Budget



Surface climate depends on heating

- 51 units of absorbed solar
- 96 units of downward infrared (almost 2x sunshine)!

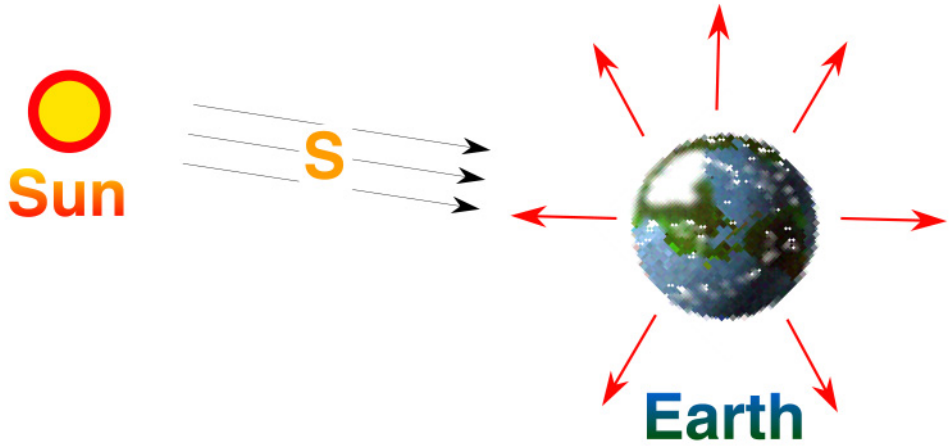
Surface climate depends on cooling

- 117 units of upward infrared
- 23 units of evaporation, 7 units of rising thermals

Climate Sensitivity

How Many Degrees of Warming per Watt/m^2 of Heating?

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

Earth's Climate as a "Black Box"

Absorbed Sunshine In

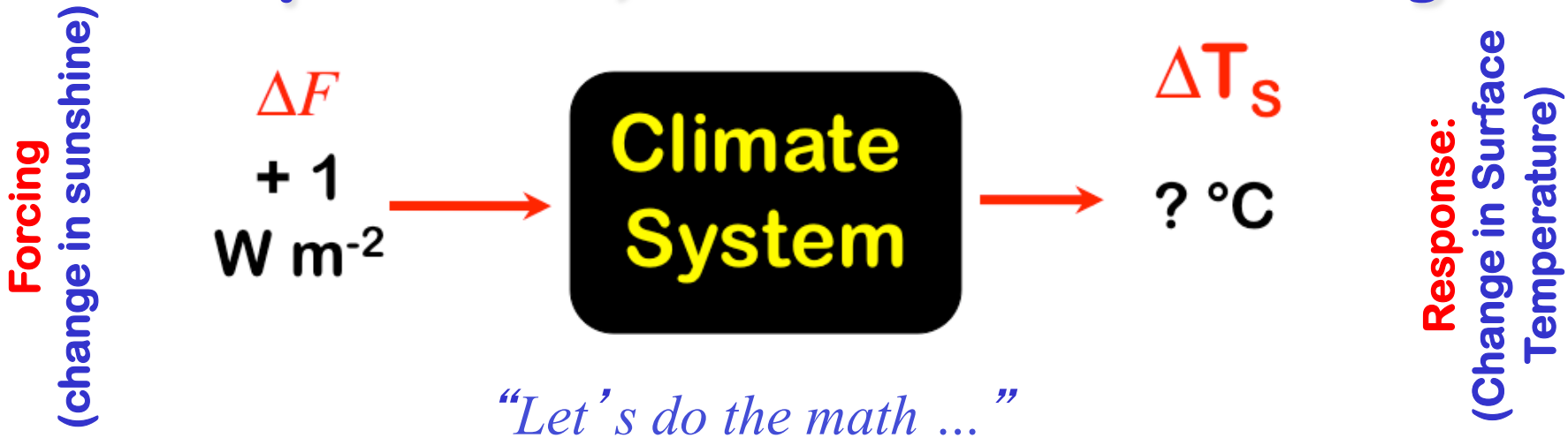
Surface Temperature Out

Climate Forcing, Response, and Sensitivity

Forcing (change in absorbed sunshine)

Response: (Change in Surface Temperature)

Climate Forcing, Response, and Sensitivity



"Let's do the math ..."

$$S_0(1-\alpha)\pi r^2 = 4\pi r^2 \sigma T^4$$

$$S_0(1-\alpha) = 4\sigma T^4$$

$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

Solve for ΔF that produces a given ΔT

Baseline Climate Sensitivity

"Let's do the math ..."

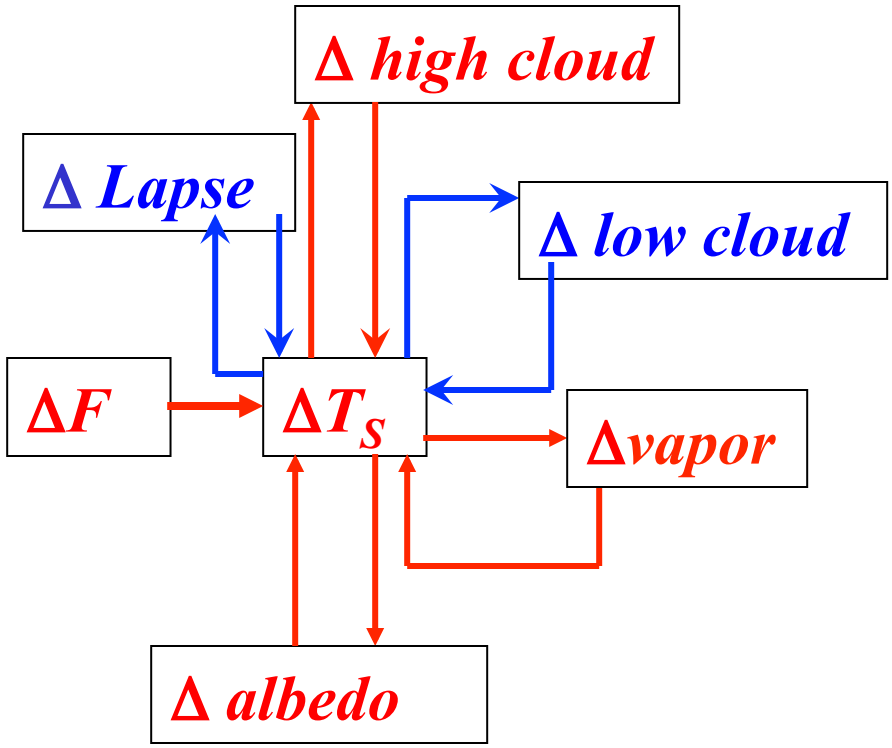
$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

$$\frac{dF}{dT} = 4\sigma T^3 = 4\sigma(255K)^3 = 3.8W\ m^{-2}K^{-1}$$

$$\Delta T = \frac{1}{3.8W\ m^{-2}K^{-1}}\Delta F = \frac{0.266\,K}{W\ m^{-2}}\Delta F$$

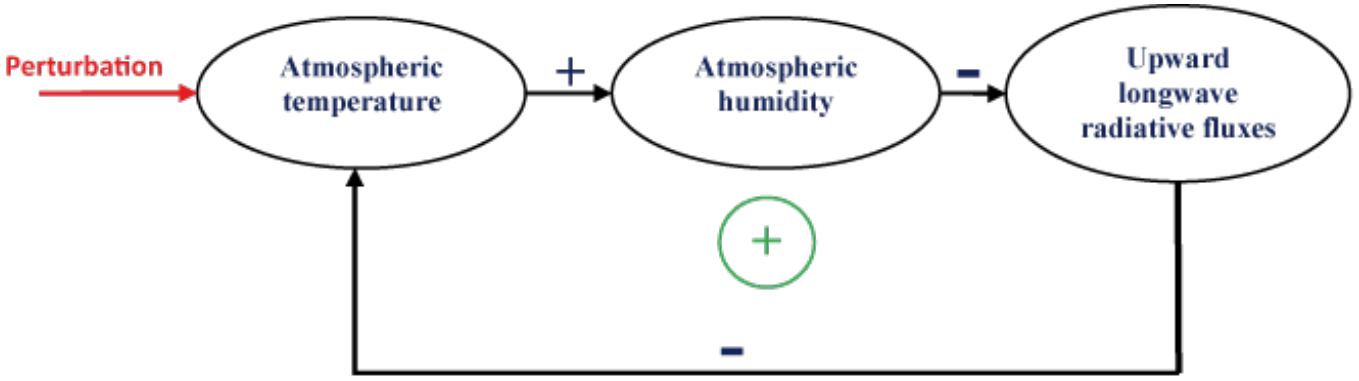
A 1 W m^{-2} change in absorbed sunshine produces about a 0.27 °C change in Earth's temperature

Climate Feedback Processes



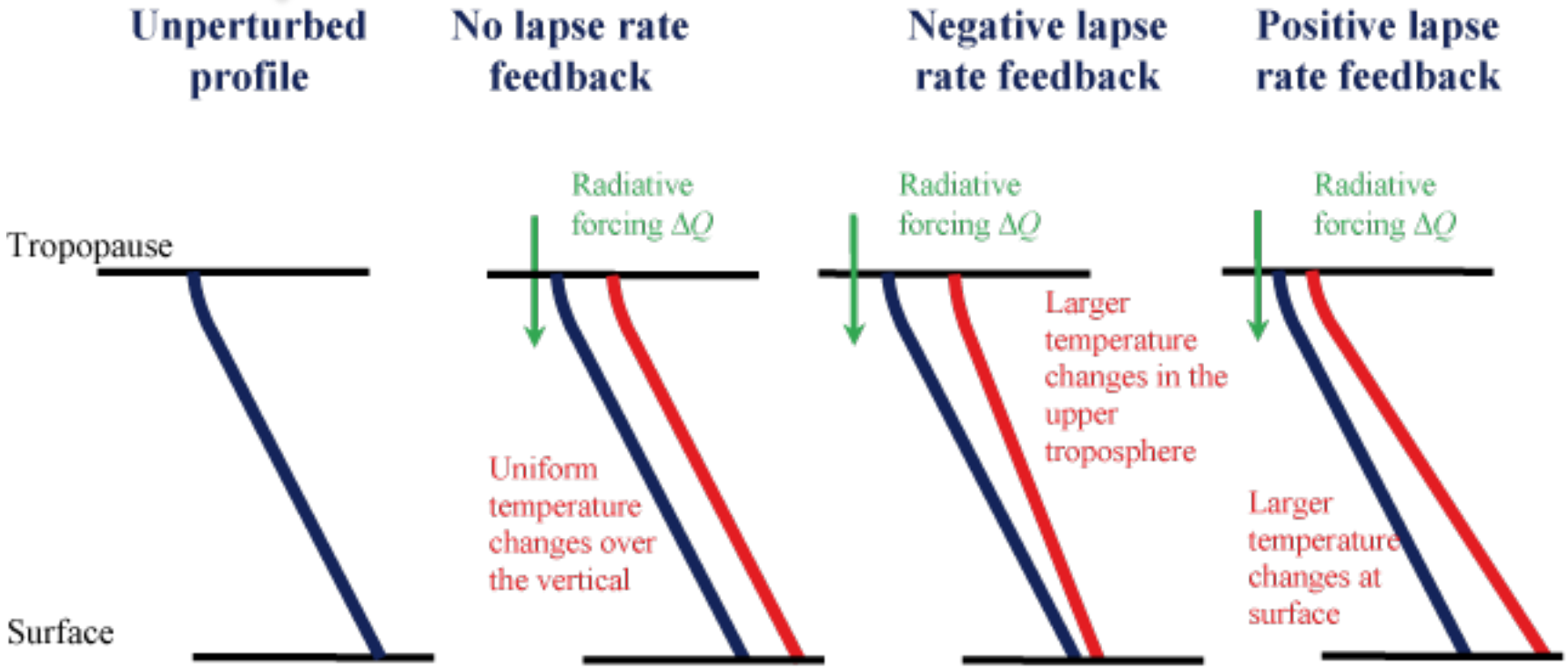
- **Positive Feedbacks (amplify changes)**
  - Water vapor
  - Ice-albedo
  - High clouds
- **Negative feedbacks (damp changes)**
  - Lapse rate
  - Low clouds

Water Vapor Feedback



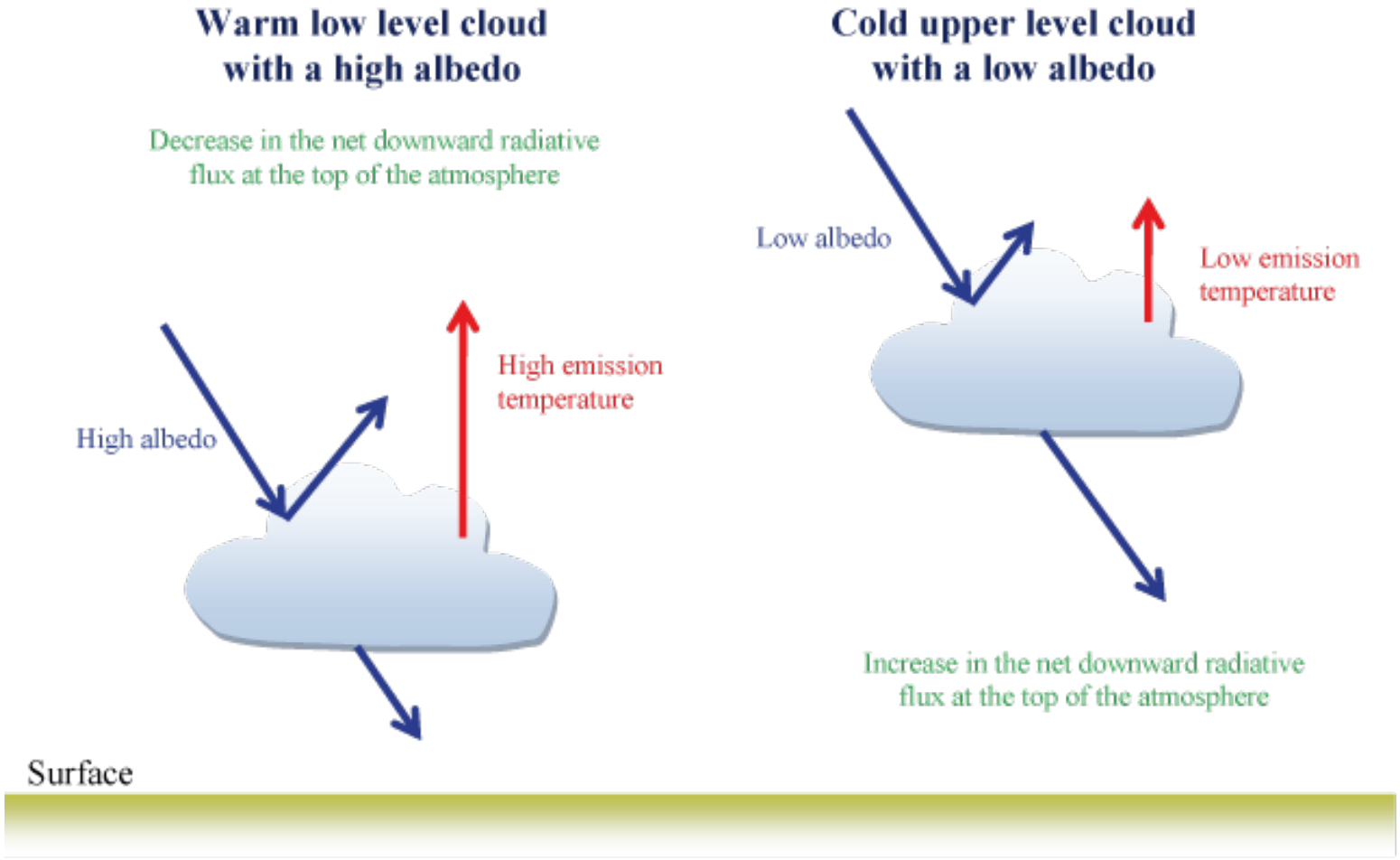
- Radiative forcing warms surface
- Warmer surface evaporates more water
- Warmer air can “hold more water”
- Increased water vapor (GHG) absorbs more outgoing radiation, amplifying warming

Lapse Rate Feedback



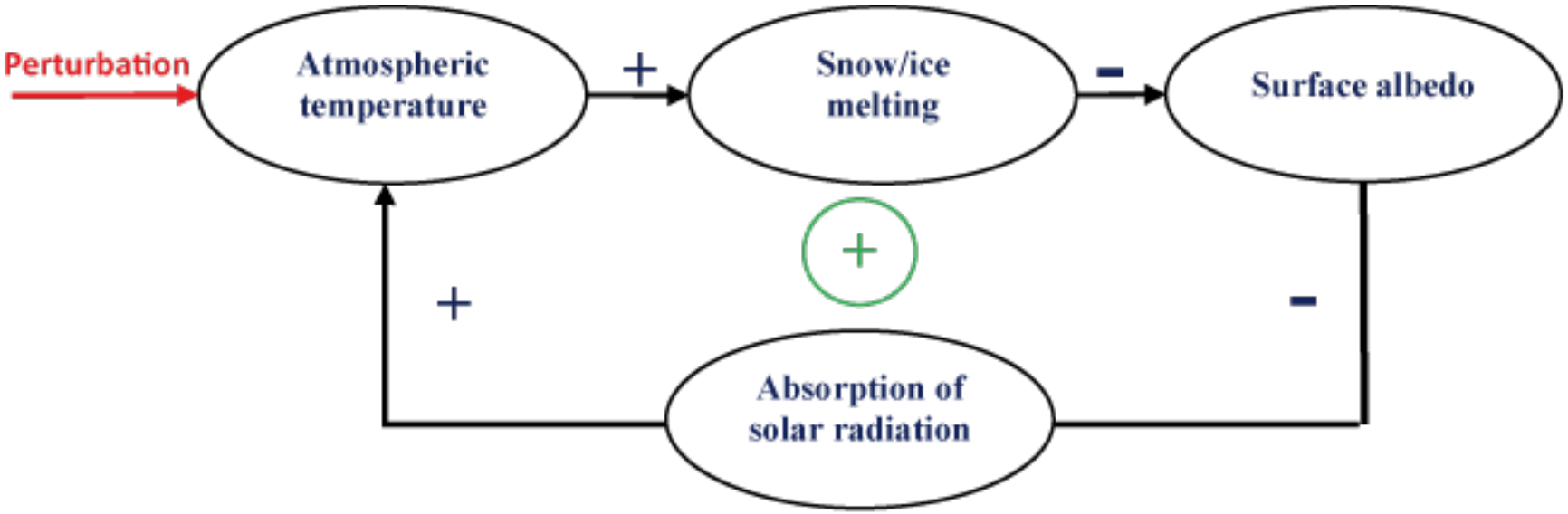
- Greenhouse effect depends on emission to space from higher (colder) levels of the atmosphere
- If radiative forcing produces increased vertical mixing by convection, then more heat is mixed to higher levels
- Warm air aloft emits more radiation to space, compensating for original forcing

Cloud Feedbacks



- Additional water vapor makes more clouds
- Low clouds cool, but high clouds warm

Ice Albedo Feedback



- Radiative forcing melts snow and ice
- Darker surface absorbs more radiation
- Amplifies warming or cooling

Estimating Total Climate Sensitivity

1. **Paleoclimate analogs: how much has climate changed in the past when forcing of known strength was applied?**
   - **Advantage: all feedbacks included**
   - **Disadvantage: hard to know exactly how much forcing & global temperature response**
2. **Calculation from physical principles including feedback processes (complex global climate models)**
   - **Advantage: Physical insight**
   - **Disadvantage: "All models are wrong …"**

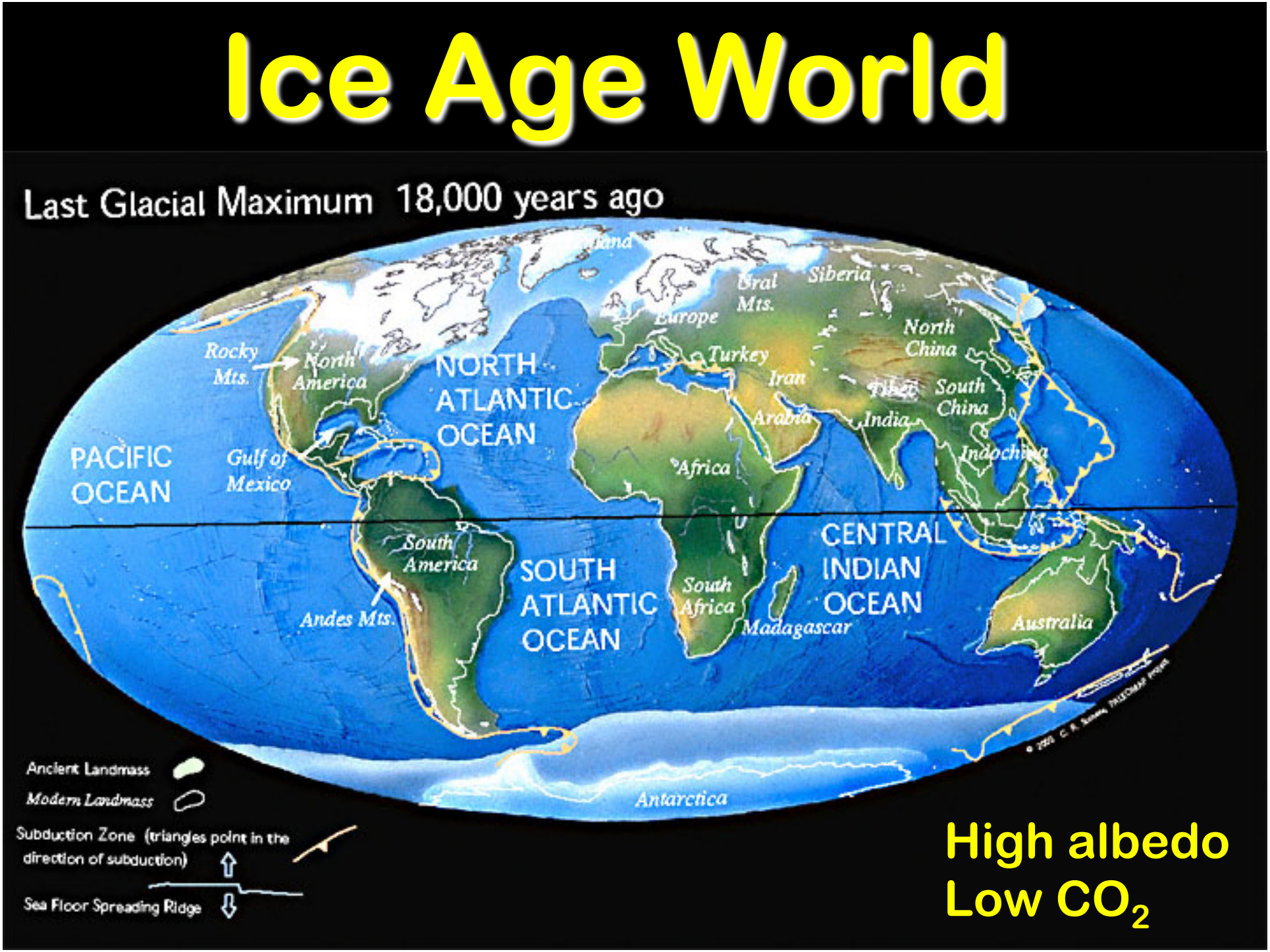
Learning from the Past

1. **Geologic past**
   (100's of millions of years)
2. **Deglaciation** analog
   (18,000 years ago to preindustrial time)
3. **Last Millennium** analog
   (Medieval Warm Period to Little Ice Age)
4. **Modern** Climate Record
   (20th Century changes)

The further back we go, the less data we have to work with.

Using modern data, we have only brief transients to study.

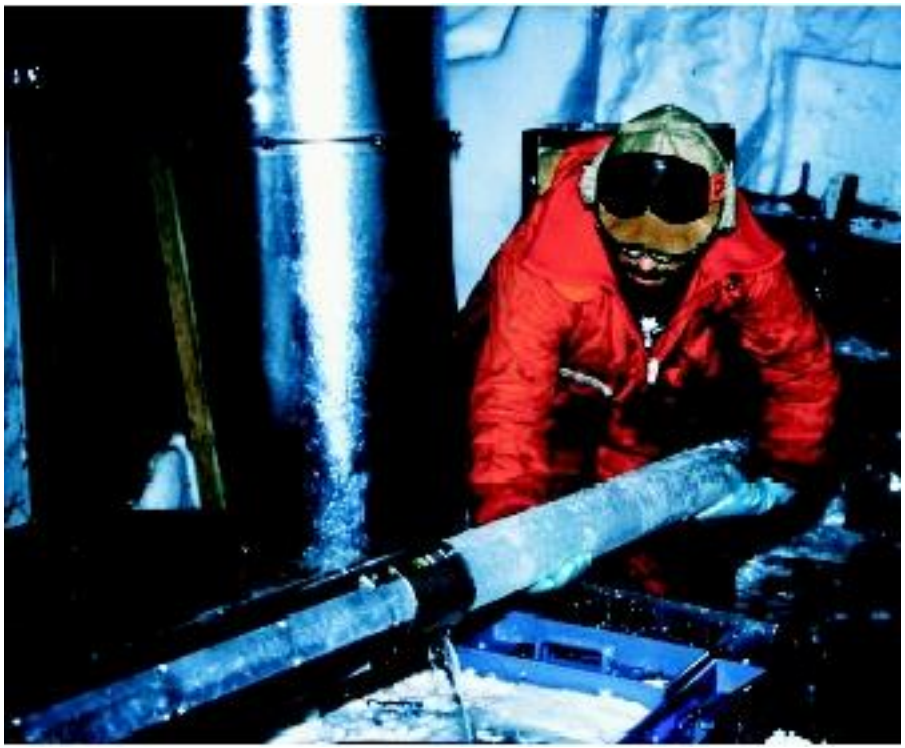
Ice Age World

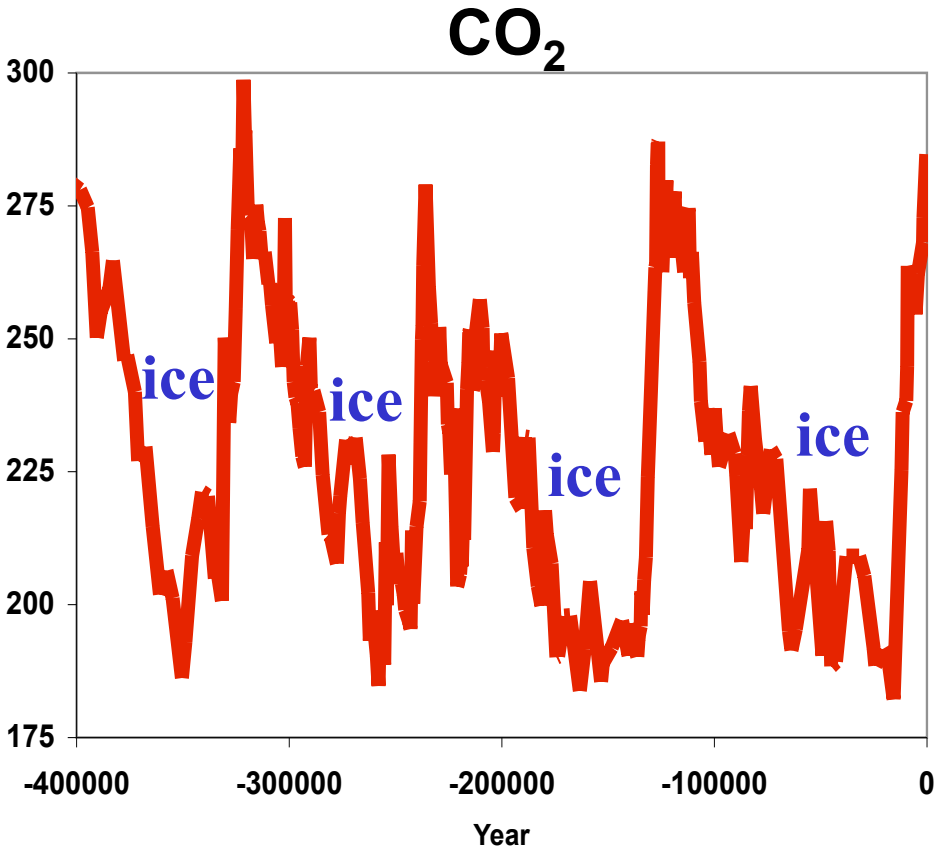


High albedo
Low CO_2

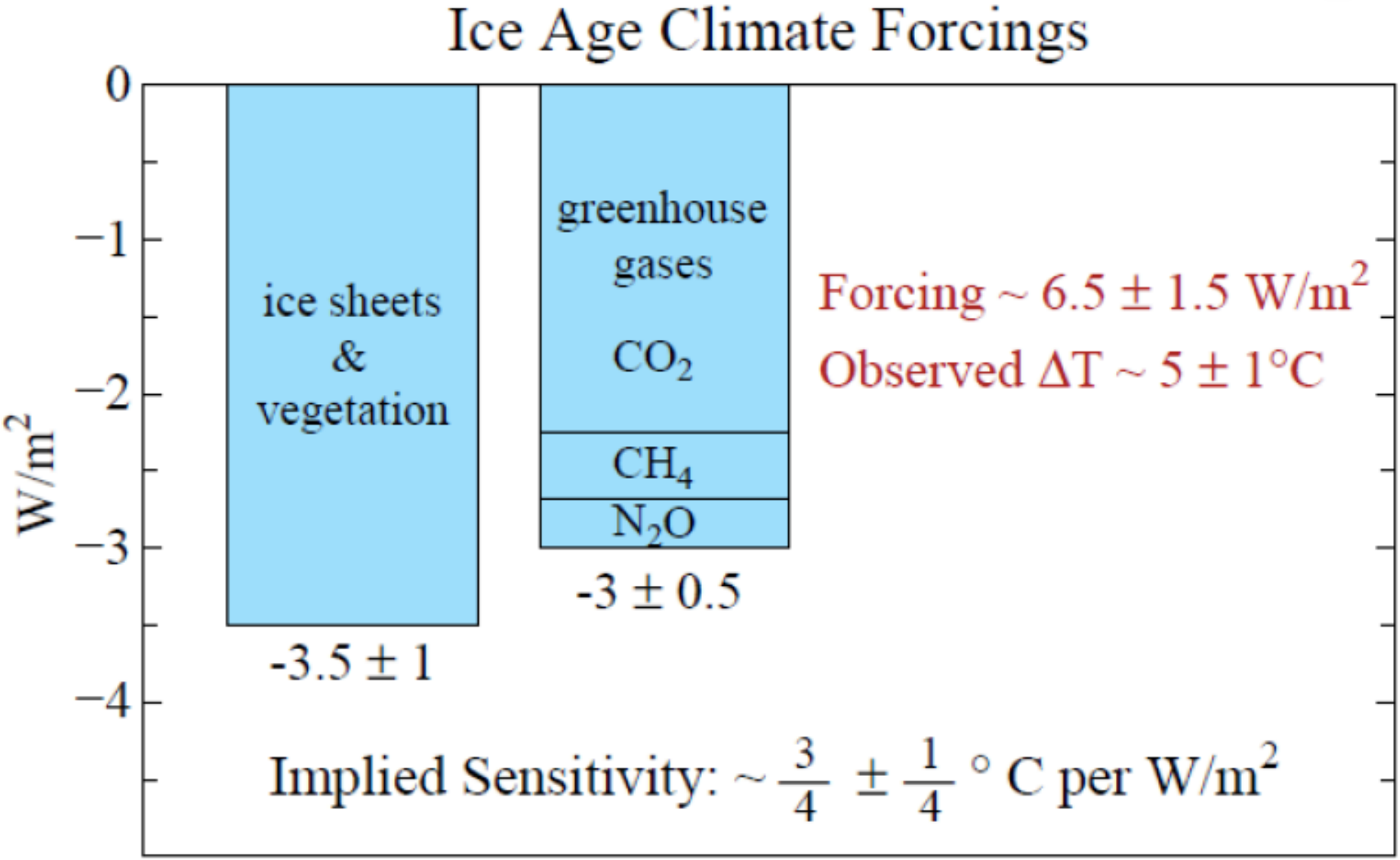
CO_2 and the Ice Ages

- Over the past 420,000 years atmospheric CO_2 has varied between 180 and 280 ppm, beating in time with the last four glacial cycles



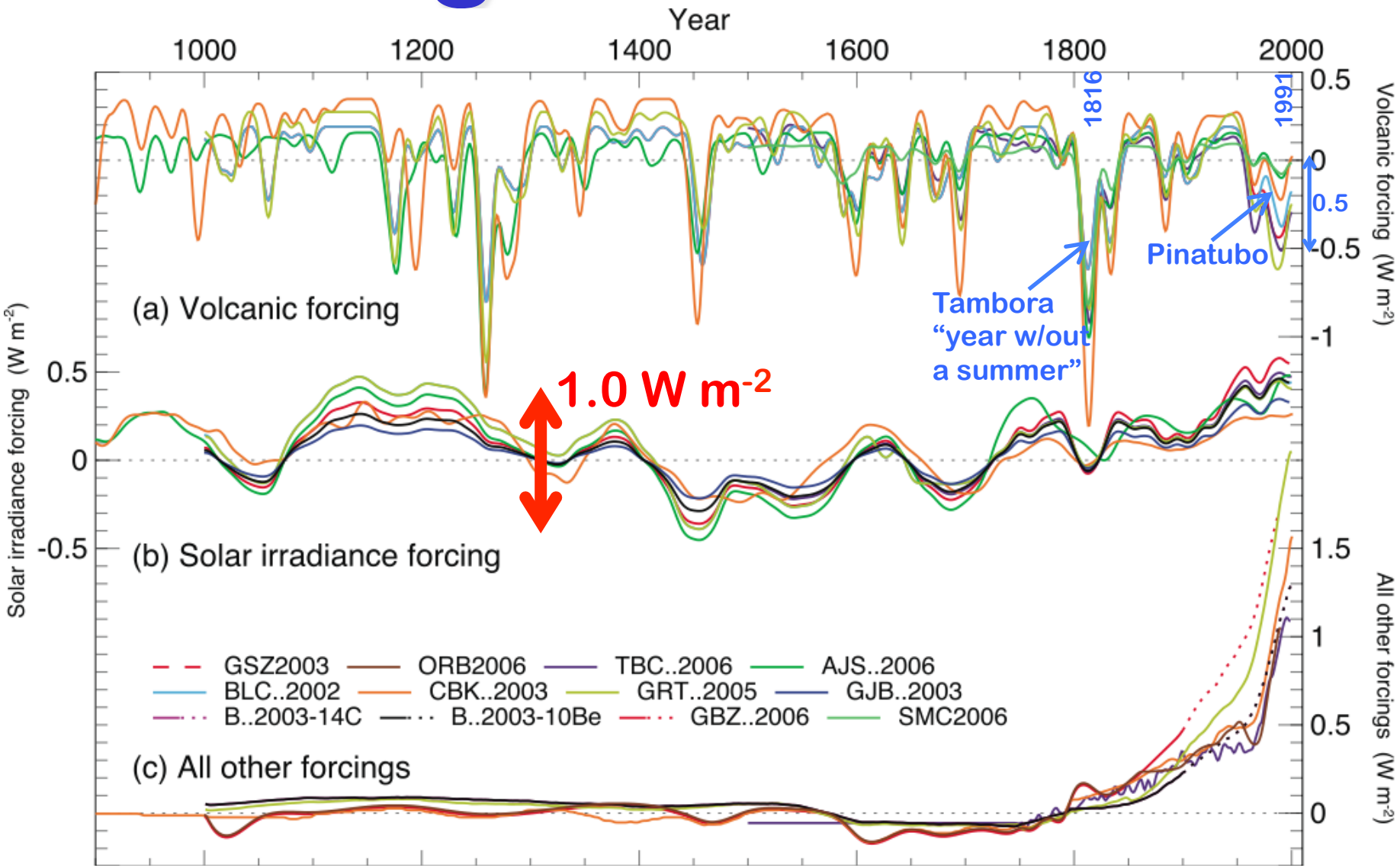


LGM Climate Forcing

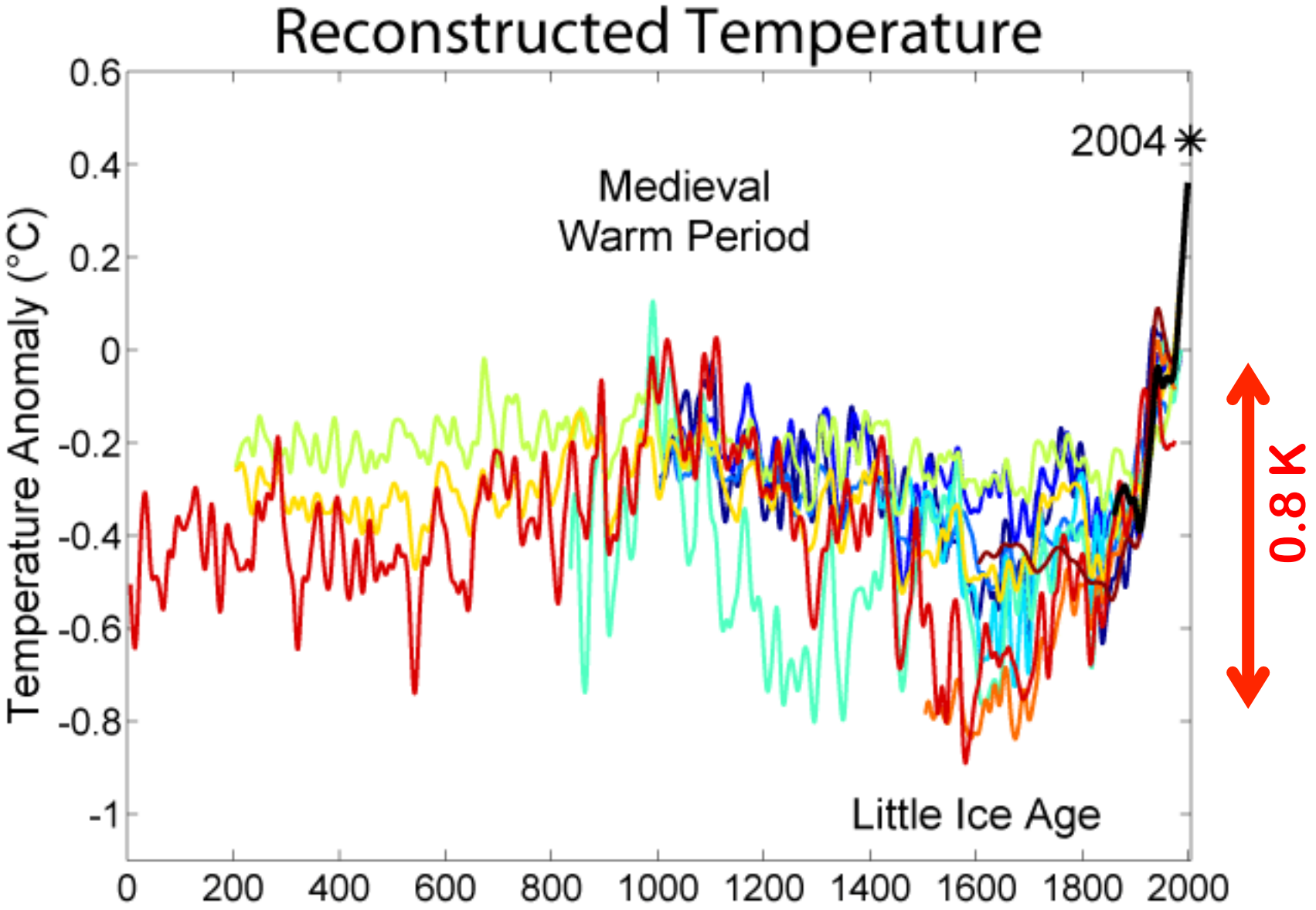


Source: Hansen and Sato (2011)

Reconstructed Climate Forcing Since 1000 AD



The Past 2000 Years



Second Millennium Analog

- Cooling from Medieval Warm Period to Little Ice Age ~ 0.8 K

- Solar forcing ~ 1.0 W m^{-2} (somewhat complicated by volcanic forcing)

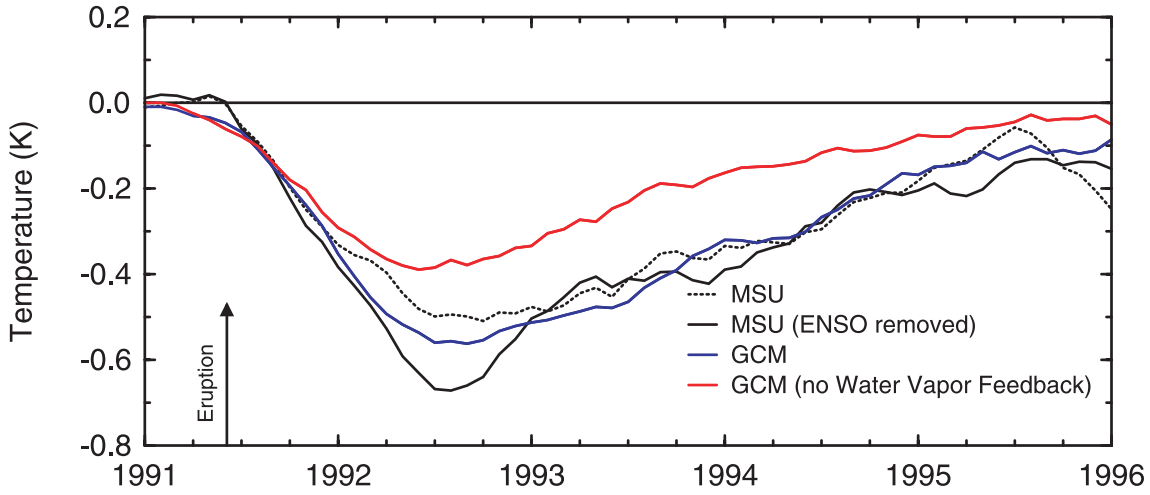
Total climate sensitivity (including feedback)

0.8 K per (W m^{-2})

A frost fair on the Thames at Temple Stairs, c 1684. Abraham Hondius Museum of London

Volcanic Analog

- Cooling following eruption of Mount Pinatubo in 1991 ~ 0.5 K
- Volcanic forcing ~ 0.7 W m^{-2}



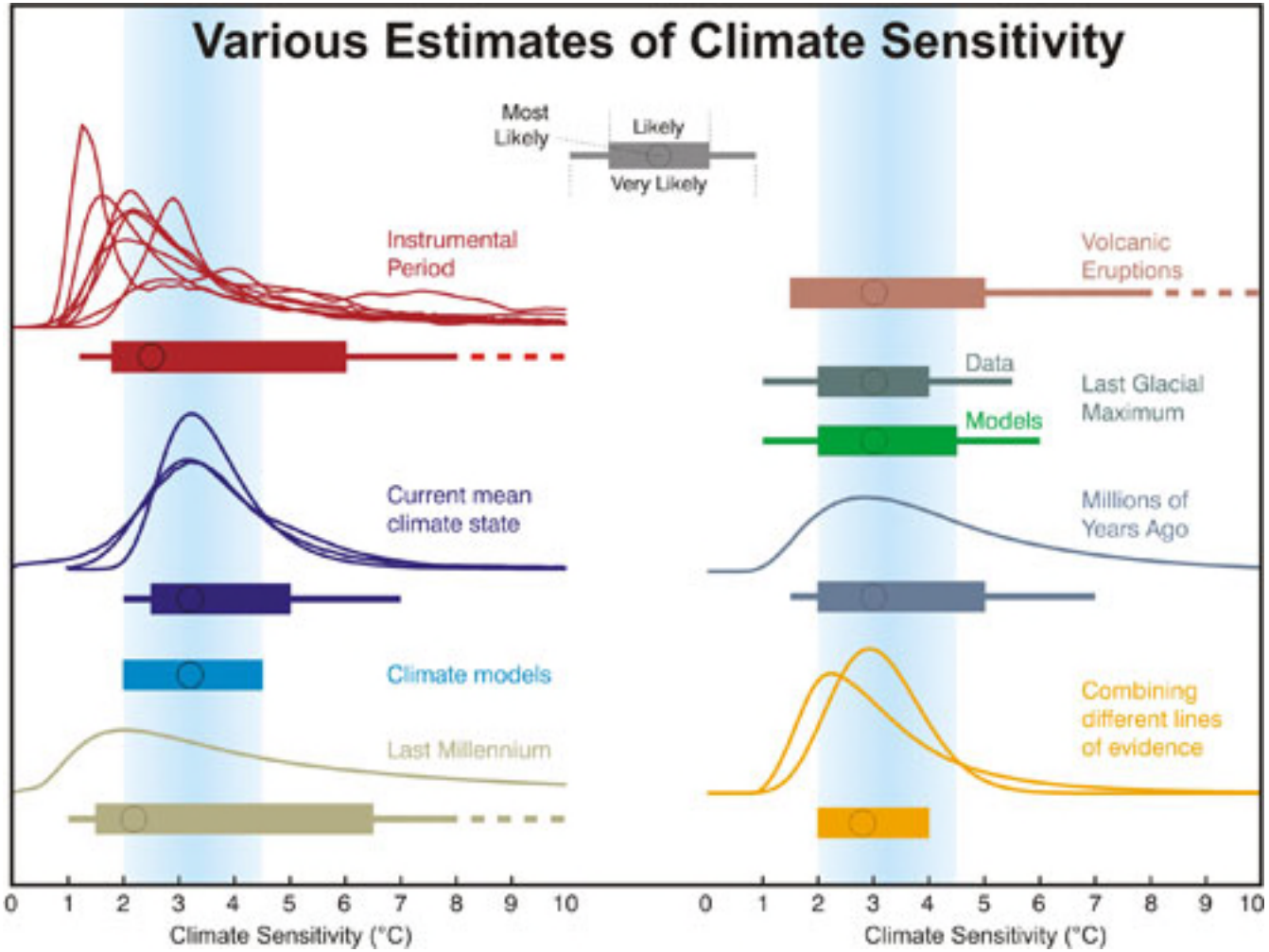
Total climate sensitivity (including feedback)

0.7 K per (W m^{-2})

Climate Sensitivity to enhanced CO_2

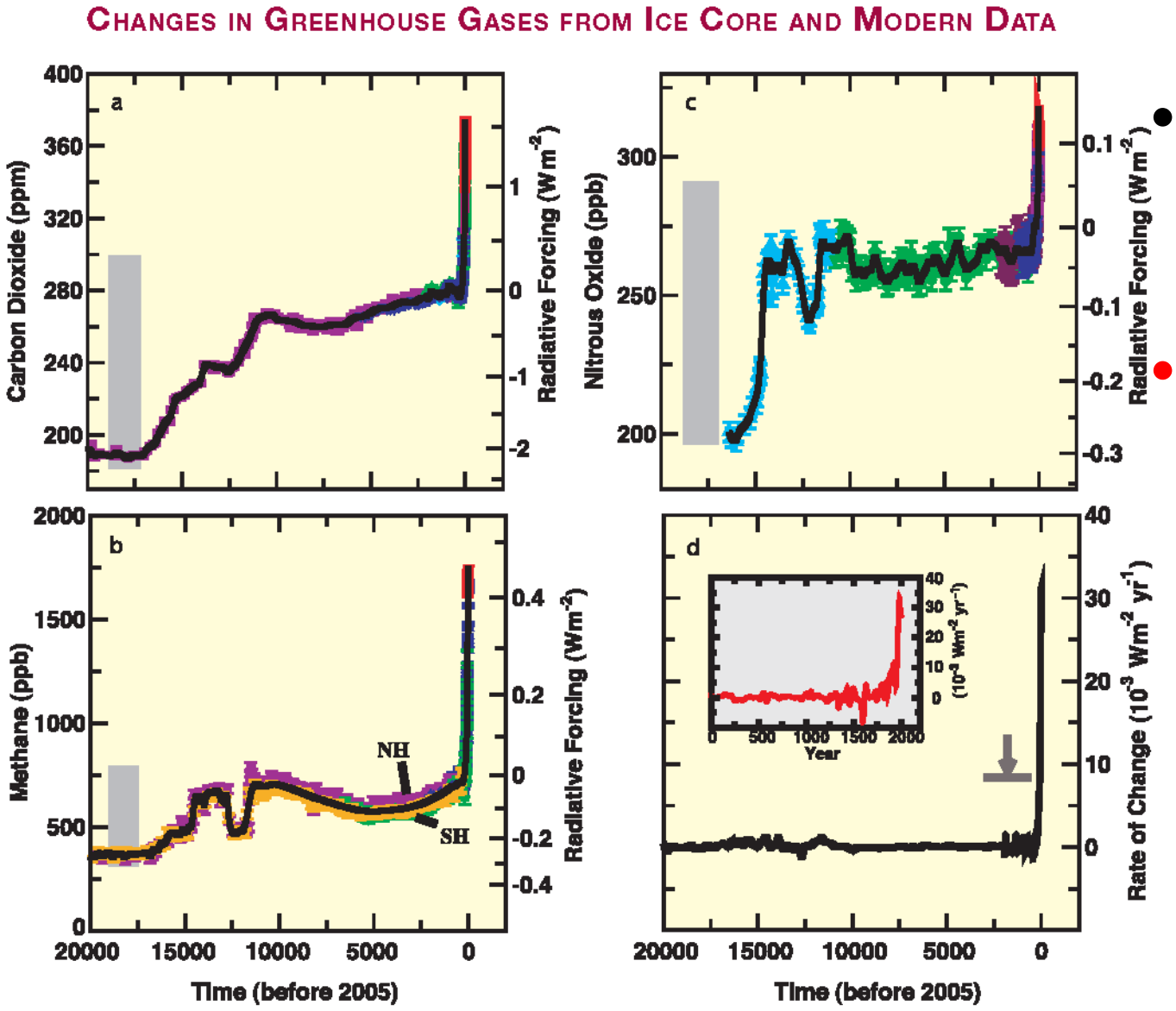
- Many lines of evidence suggest about 0.8 °C of warming per ($W\ m^{-2}$)
- Remember each doubling of CO_2 adds 3.7 Watts per square meter
- So expect about
  ($3.7\ W\ m^{-2}$) x ($0.8\ °C\ (W\ m^{-2})^{-1}$)
  = 3 °C per doubling of CO_2

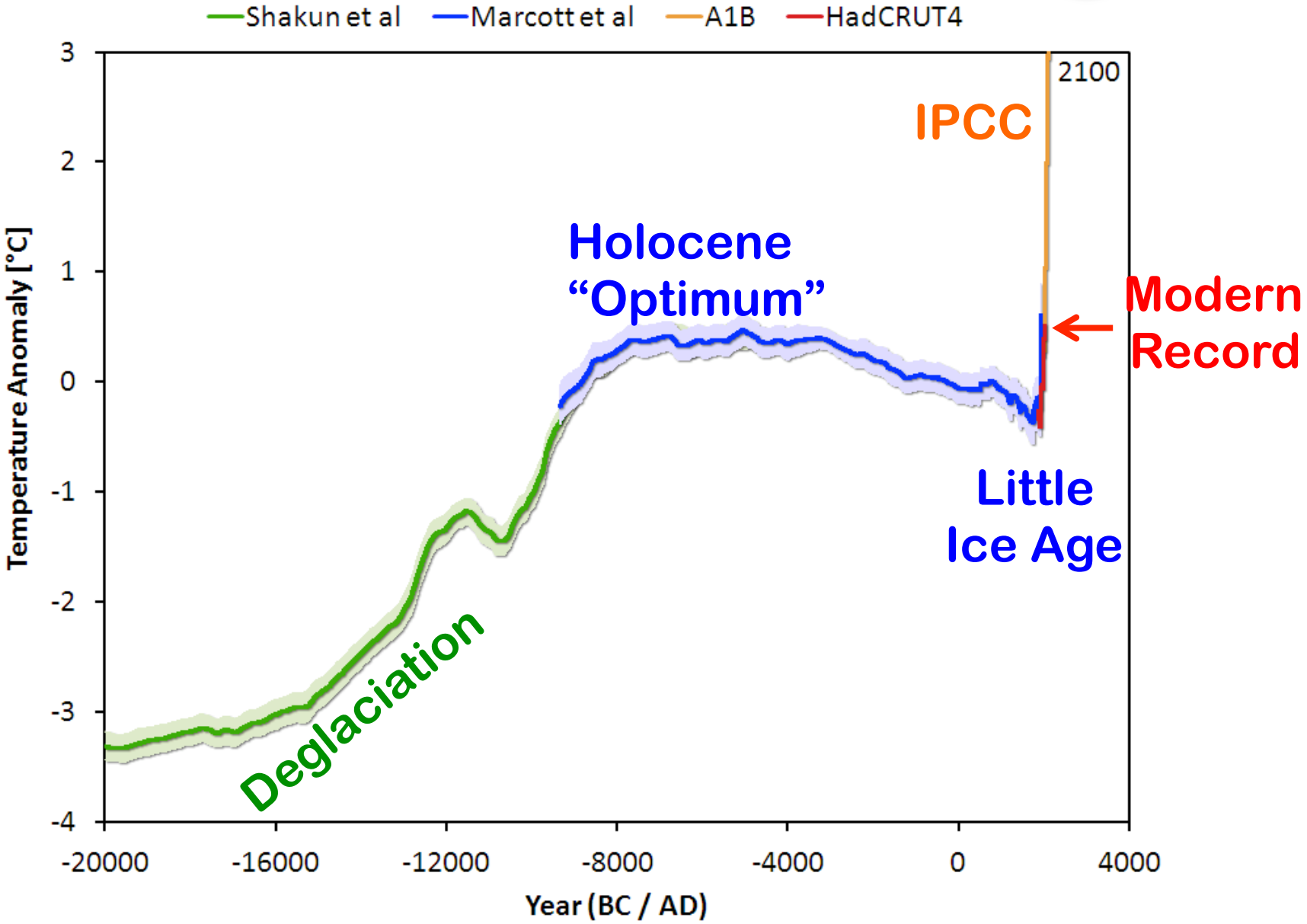
Climate Sensitivity



Distributions and ranges for climate sensitivity from different lines of evidence. The circle indicates the most likely value. The thin colored bars indicate very likely value (more than 90% probability). The thicker colored bars indicate likely values (more than 66% probability). Dashed lines indicate no robust constraint on an upper bound. The IPCC likely range (2 to 4.5°C) and most likely value (3°C) are indicated by the vertical grey bar and black line, respectively (Source: Knutti & Hegerl, Nature, 2008)

GHG Radiative Forcing



- Note different scales
- Modern changes comparable to postglacial, but much faster!

Since the Ice Age