# Fundamentals of Climate Change (PCC 587): Radiation

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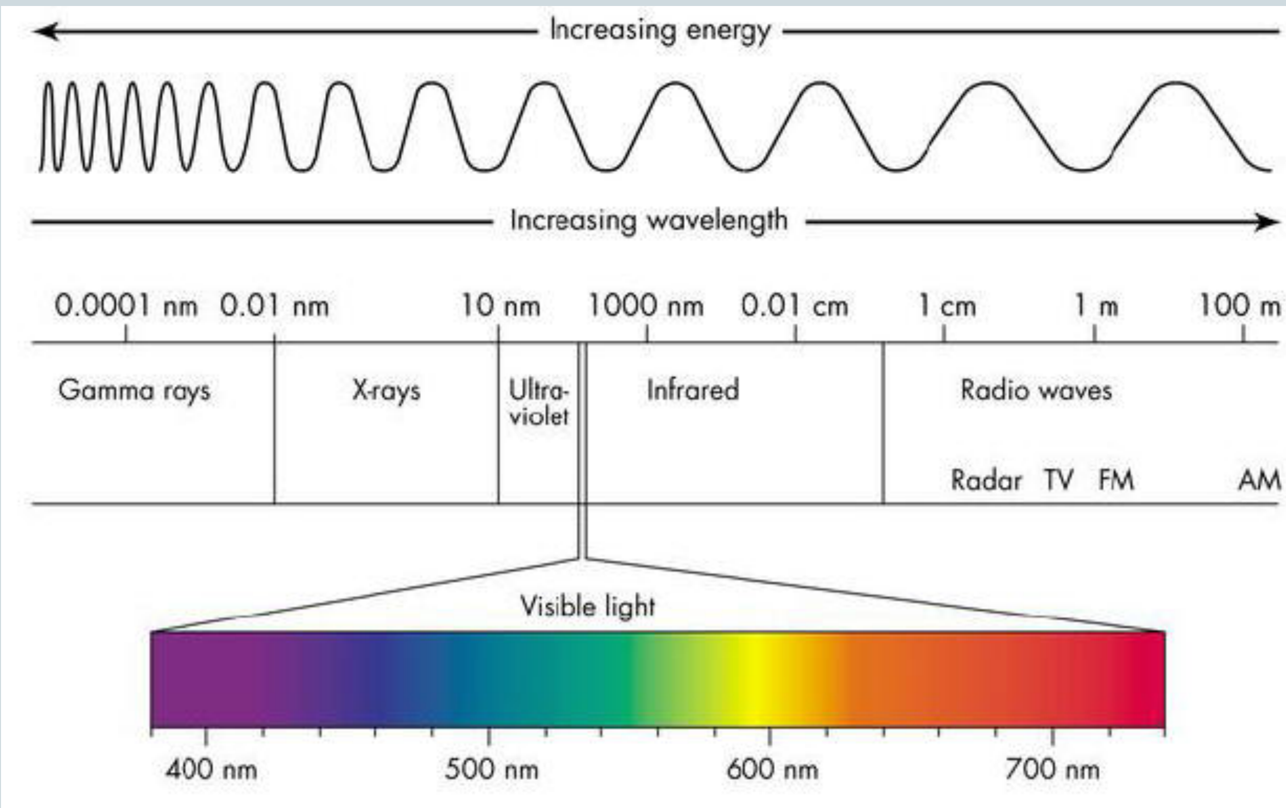
DAY 1: 9/25/13

# Readings

- Archer Chap 2: Blackbody Radiation
- Archer Chap 3: The Greenhouse effect
- Archer Chap 4: Greenhouse Gases

# Today: Radiative Transfer

- Radiation = light
  - Visible or otherwise…



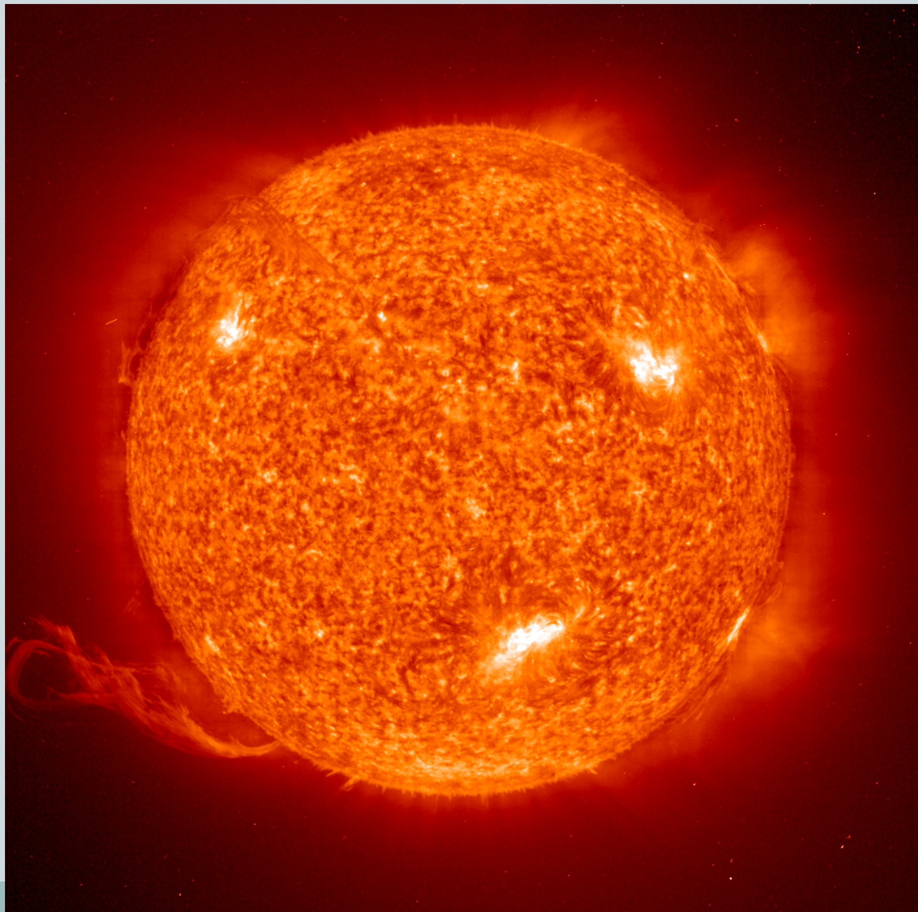

Shorter wavelengths => more energetic

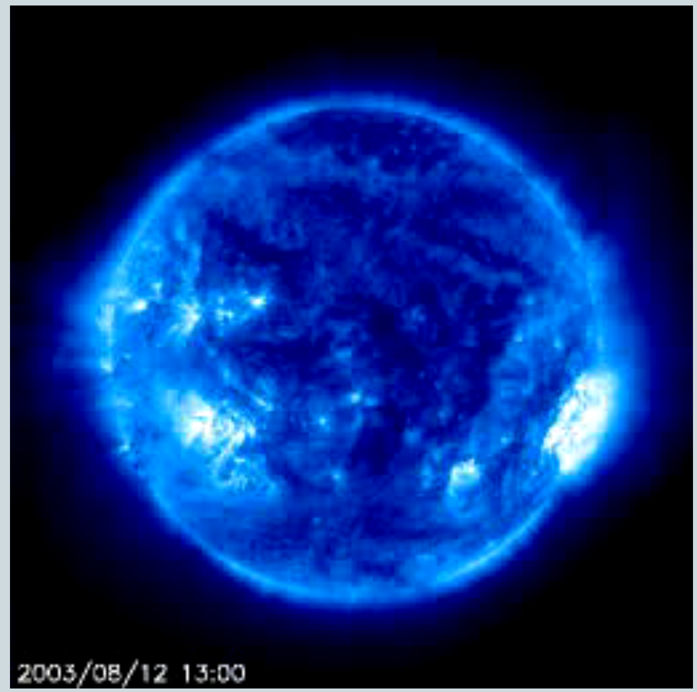
# Today: Radiative Transfer

- The sun
- Solar radiation interacting with the Earth
  - Reflection, absorption
  - Effects of clouds, volcanoes, etc
- How the Earth radiates away heat
  - Greenhouse effect
  - Effect of $CO_2$, water vapor, etc
- All this discussion will be globally averaged
  - Later we'll start talking about tropics vs poles, etc…

# Solar Radiation

- Driver of everything in the climate system!

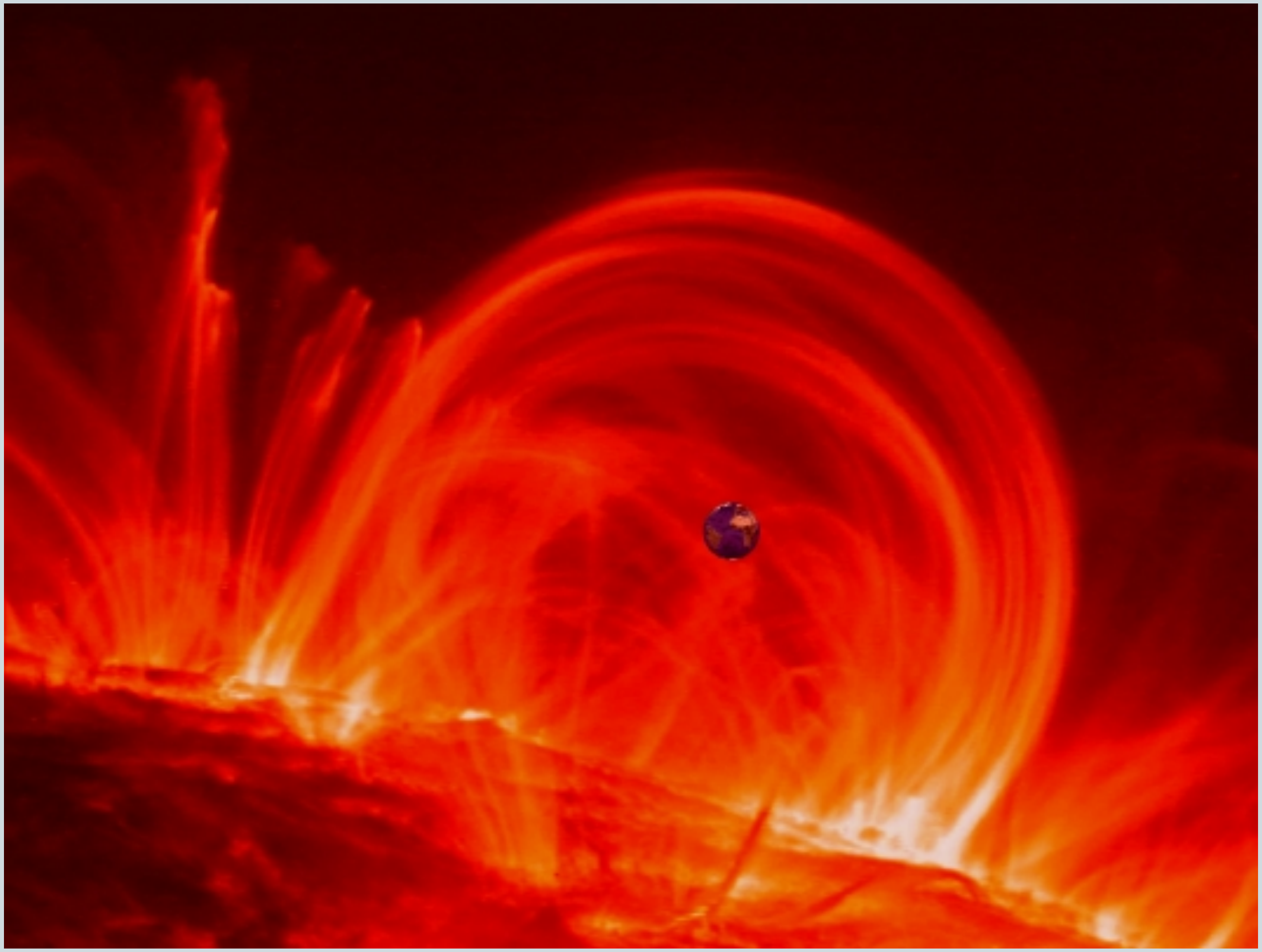




# We Are Small!

Sun is
~100 x Earth radius
~1e6 x Earth volume
~3e5 x Earth mass

10 light minutes away from Earth (100 Sun diameters away)



# Basics of Radiative Transfer

- "Black-body" radiation
  - A body that absorbs all light
- Temperature of black body determines everything
  - Intensity and color (wavelength) of radiation
  - Hotter => shorter wavelengths and much more intense

Stefan-Boltzmann Law:

$$E = \sigma T^4$$

E = total intensity
T = temperature
$\sigma$ = Stefan-Boltzmann constant
= 5.67x10^-8 W/m^2/K^4

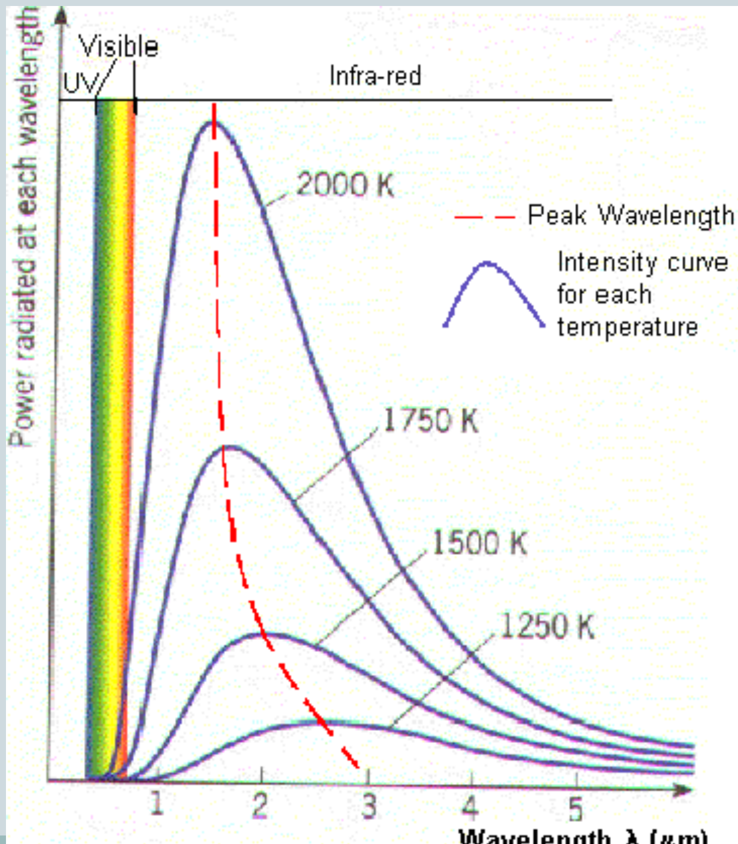
Wien's Displacement Law:

$$\lambda_{max} = b/T$$

T = temperature
$\lambda_{max}$ = wavelength at which maximum emission occurs
b = 2.897x10^-3 m K

# Black-body Radiation

- Planck's Law tells the intensity as a function of wavelength for each temperature:




Stefan-Boltzmann Law tells you the integral under the blue curves (total emission over all wavelengths)

Wien's Displacement Law tells you the peak emission wavelength (dashed red)

# Thermal Radiation

- At normal Earth temperatures, the thermal emission is infrared (we can't see it)

Infrared imaging shows us the temperatures of stuff:
e.g., cold nose, warmer eyes and ears

# Thermal Radiation

- At temperatures around 800 K, solids glow a dim red
- 1000 K => red
- 6000 K => white (this is around the temperature of the sun's photosphere)

Can tell the temperature of lava from its color

# Solar Radiation

- 5780 K blackbody is good approximation to solar radiation



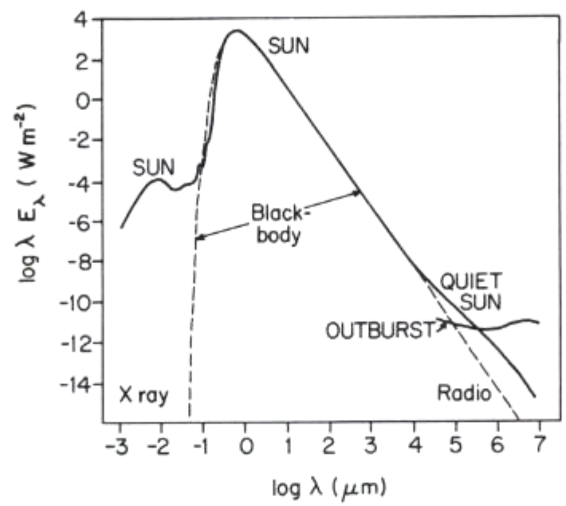
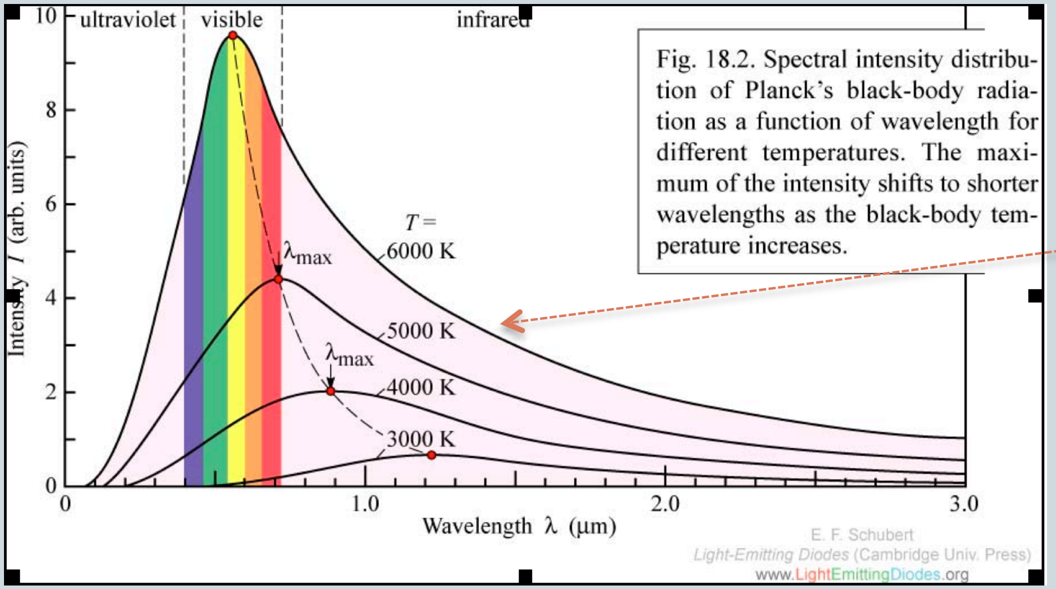



**Fig. 7.2** The spectrum of the sun (——) and a black body at 5780°K (– – –). Note that in this representation the area under the curve is not proportional to irradiance. [Adapted from *Quart. J. Roy. Meteor. Soc.* **84**, 311 (1958).]

Houghton 2002

# Spectrum of the Sun's Radiation

- Solar radiation is mostly in the visible bands

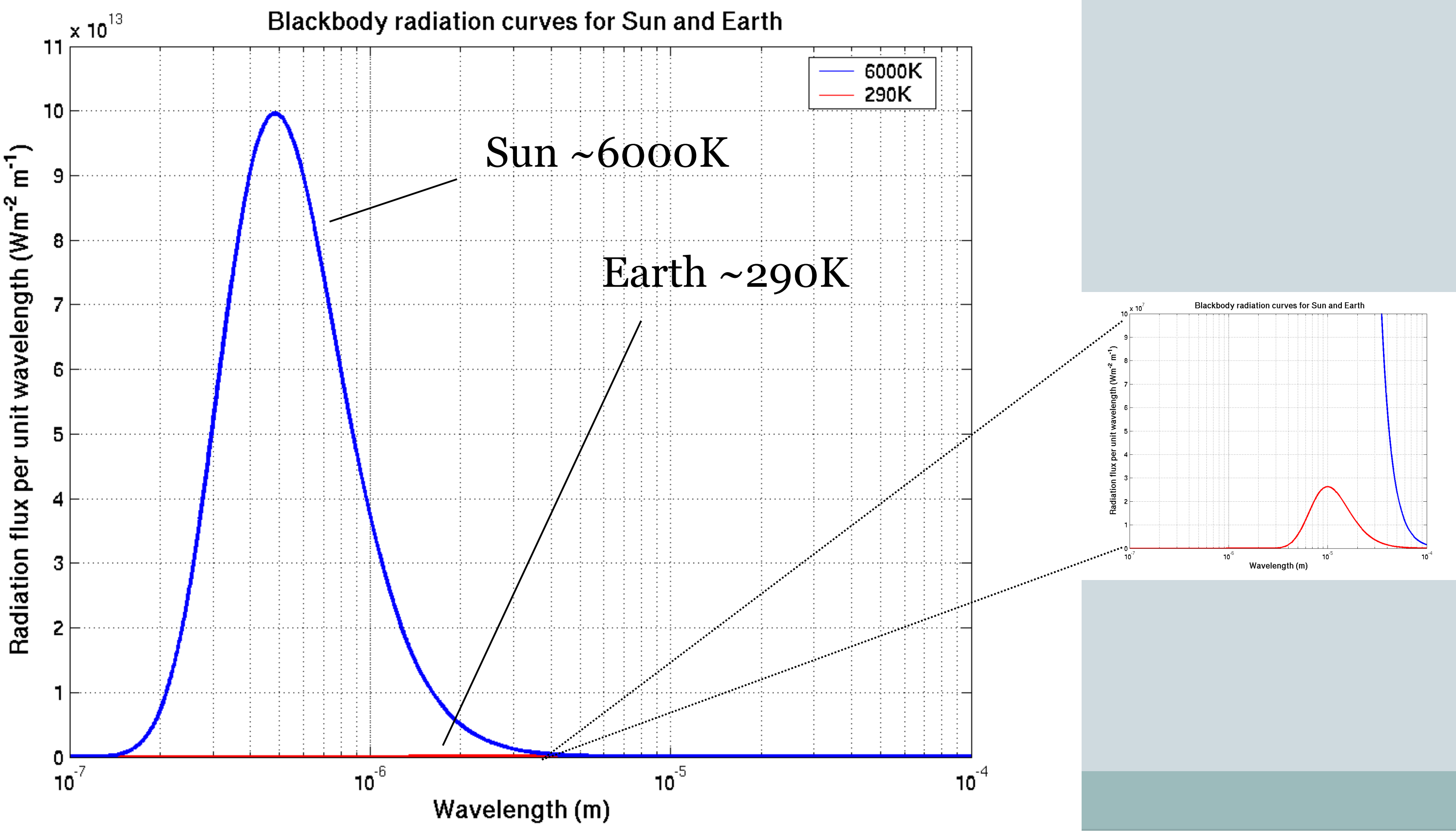



Top curve is close to what the sun emits

- Also significant UV and infrared emission by the sun

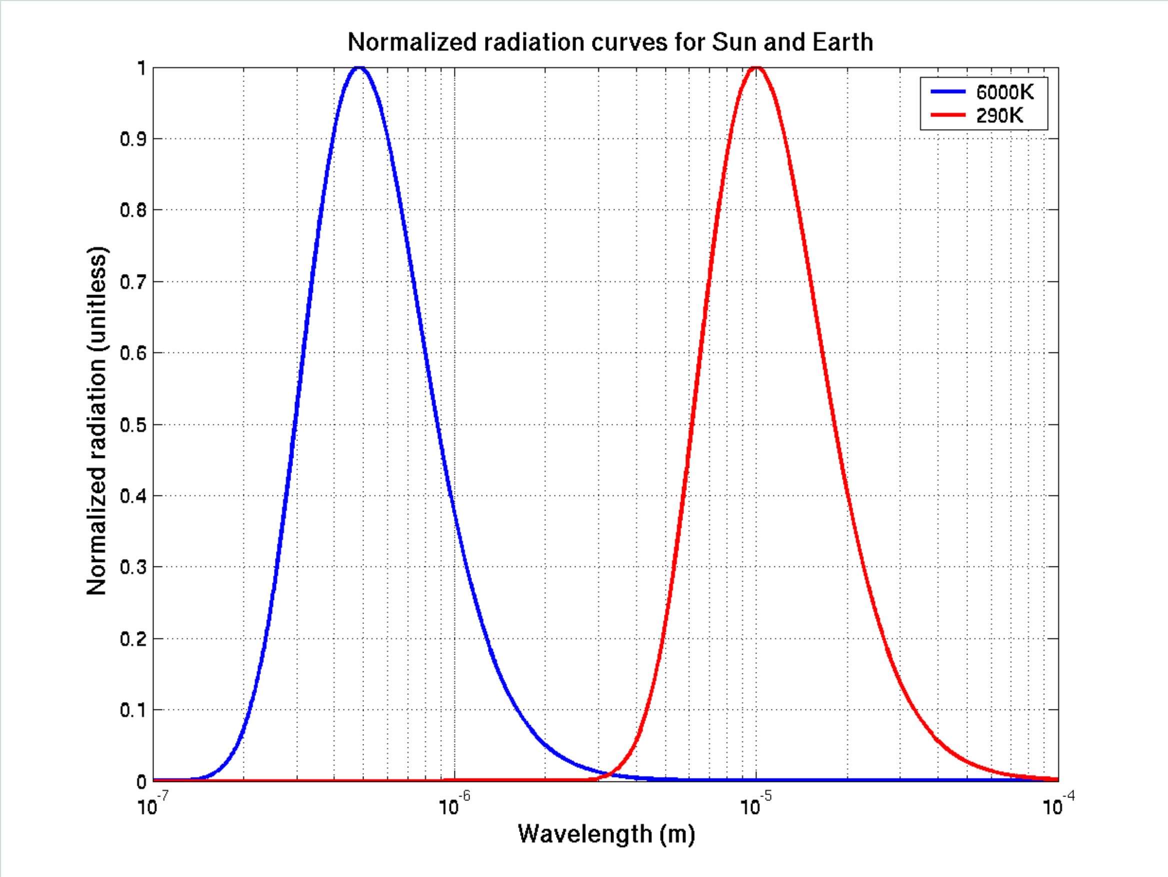
# Solar Radiation

- Sun emits way more radiation than the Earth!



# Solar vs Terrestrial Radiation

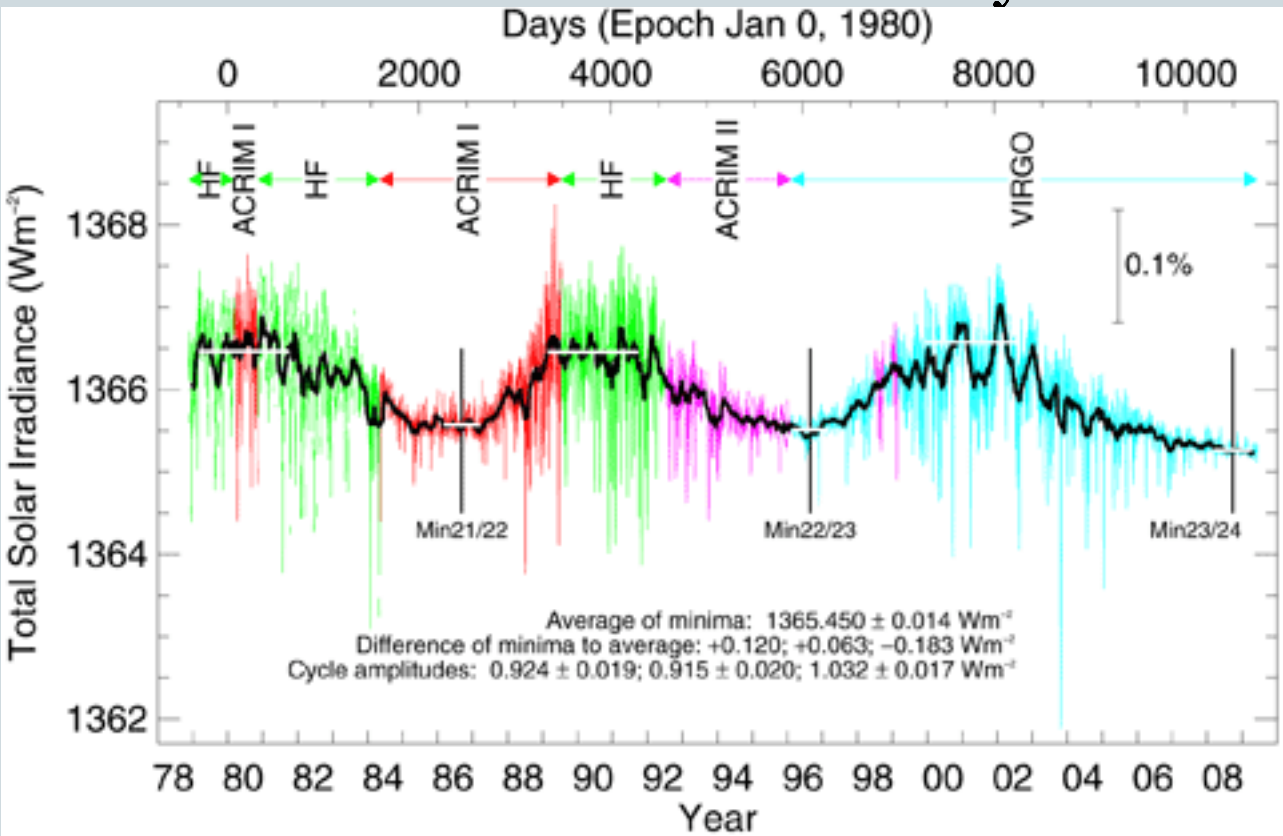
- Normalize the curves so maximum intensities are equal:




Very little overlap: solar ("shortwave") and Earth ("longwave")

# Variability of Solar Output

- Solar constant varies over 11 year sunspot cycle:




Variability is around 0.07% over 11 yr period

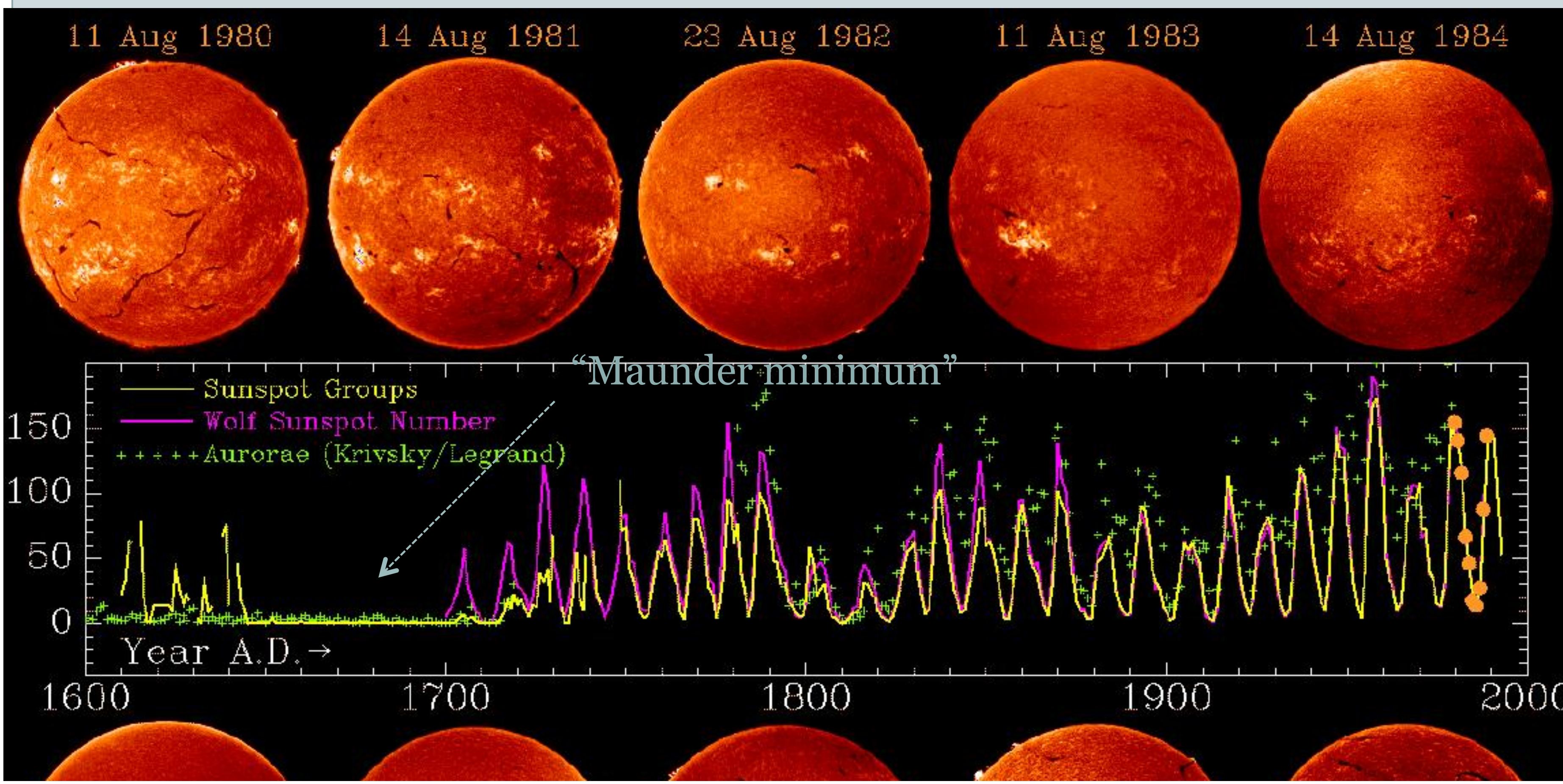
Affects global temperatures by 0.2 K? (research of KK Tung, Applied Math)

We are just recovering from a prolonged minimum in solar activity

- Note high frequency variability as well

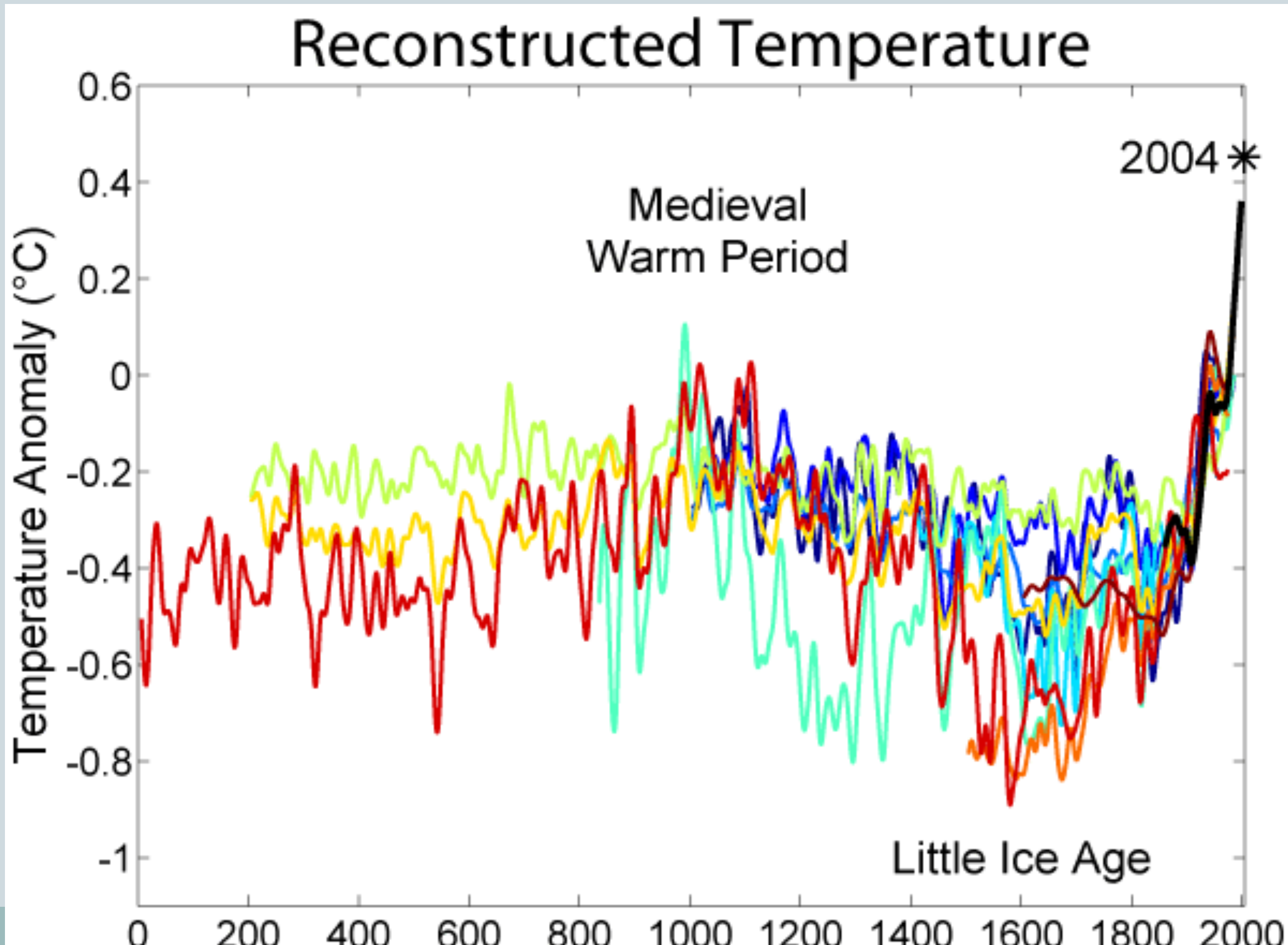
# Sunspot Cycles over Time

- Sunspots have longer period variability than just the 11 year cycle:



# Sunspot Cycles over Time

- Maunder minimum coincides with "Little Ice Age"?

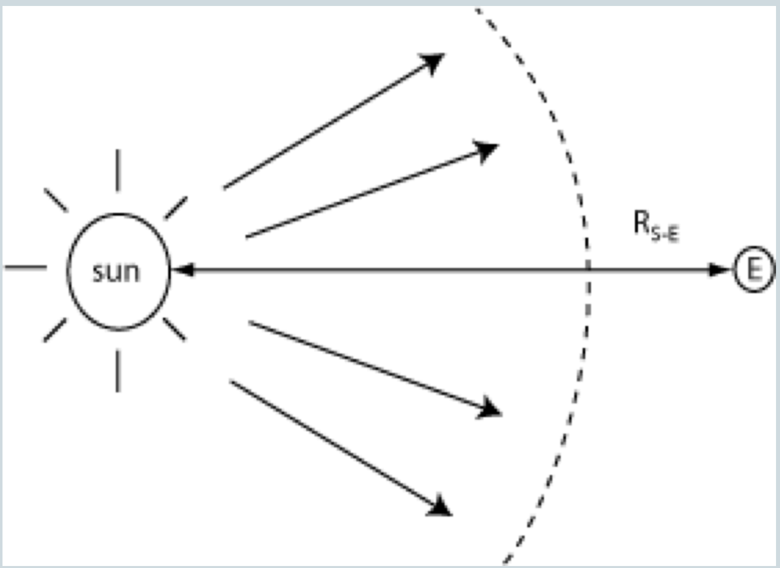



There was also enhanced volcanic activity at this time

Source: Global Warming Art

# Solar Radiation and Earth

- Insolation felt on Earth depends on distance from the Sun




Solar radiation at Earth-sun distance (solar constant) = 1364 Watts/meter^2

Average radiation on Earth:
half of Earth is **dark** always and most locations don't receive direct radiation

Average radiation on Earth
= solar constant/4
= 341 W/m^2

- Total power from sun: 1.7 x 10^17 Watts (170 PW)
  - Comparisons: Grand Coolee Dam =6.8 x 10^9 W
  - Total power consumption of globe = 1.6 x 10^13 W

# Next Section: Solar Radiation and Earth

- What happens to the Sun's radiation when it reaches the Earth's atmosphere?
- The atmosphere is made up of
  - 78% nitrogen
  - 21% oxygen
  - 1% argon
  - 0.4% water vapor (varies a lot with location though)

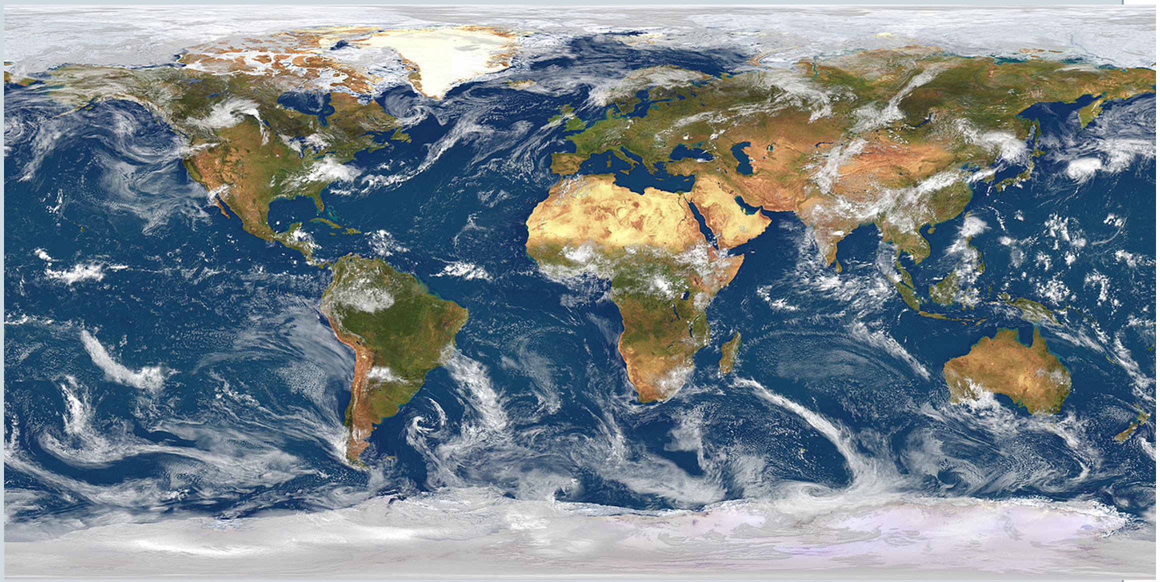
- The important ones for radiation are all a tiny fraction of atmospheric mass (**trace gases**):
  - Water vapor, CO2, ozone, etc

# Solar Radiation and Earth

- When the Sun's radiation reaches the Earth's atmosphere, several things can happen:
  - Scattering/reflection of solar radiation
  - Absorption
  - Transmission
- Most solar radiation makes it straight to the surface
  - **50%** of top-of-atmosphere (TOA) radiation is **absorbed at the surface**
  - 20% is absorbed in atmosphere (17% in troposphere, 3% in stratosphere)
  - **30%** is **reflected** back to space (25% by atmosphere, 5% by surface)

# What does the reflection?

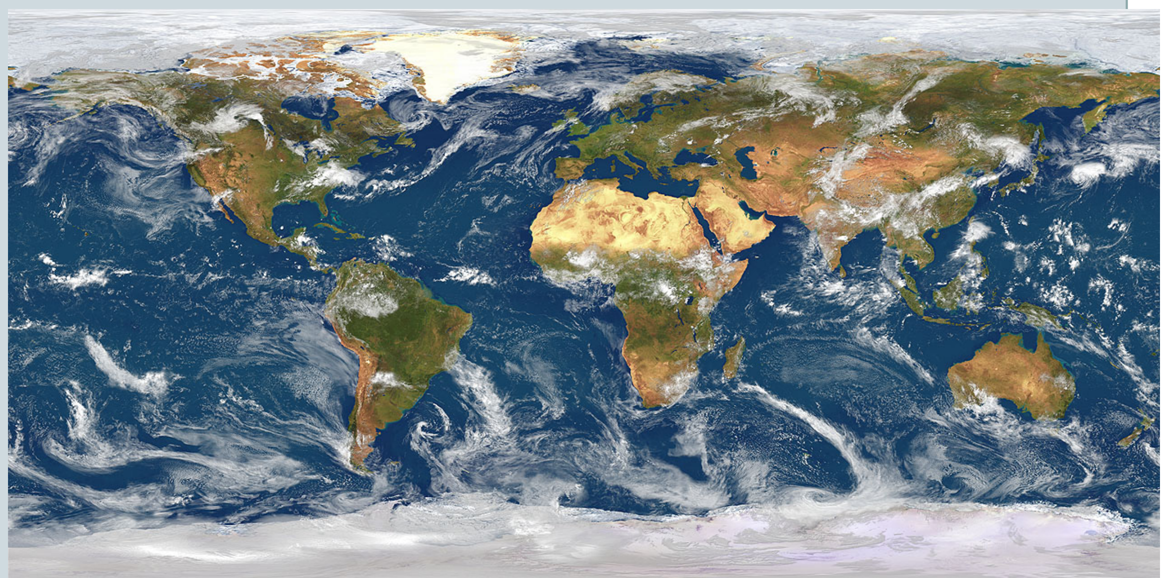
- **Clouds** reflect the most solar radiation by far
  - 2/3 reflection by clouds
  - 1/6 reflection by clear sky atmosphere
  - 1/6 reflection by surface



(Remember poles are exaggerated in Mercator projections like this)

# Albedo

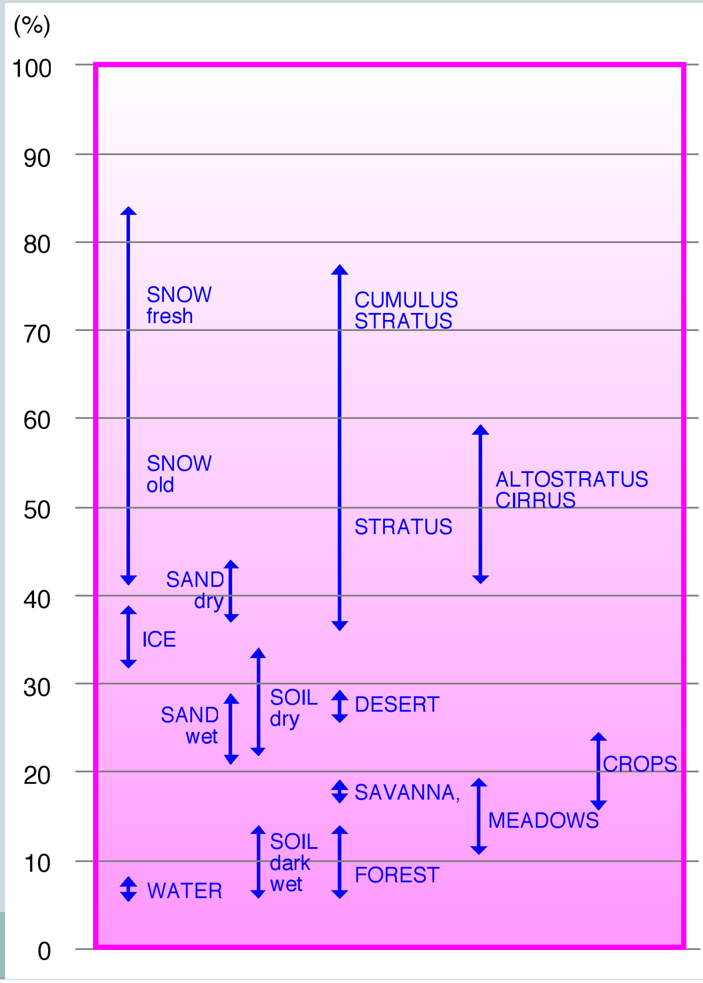
- Albedo: reflectivity of a surface
  - Black = 0, white = 1
- Cloud albedo depends primarily on thickness (0.2-0.7)
- Snow albedo: 0.4-0.9 (depending mostly on age)
- Ocean is very dark (< 0.1)
- Desert ~ 0.3, forest ~ 0.15



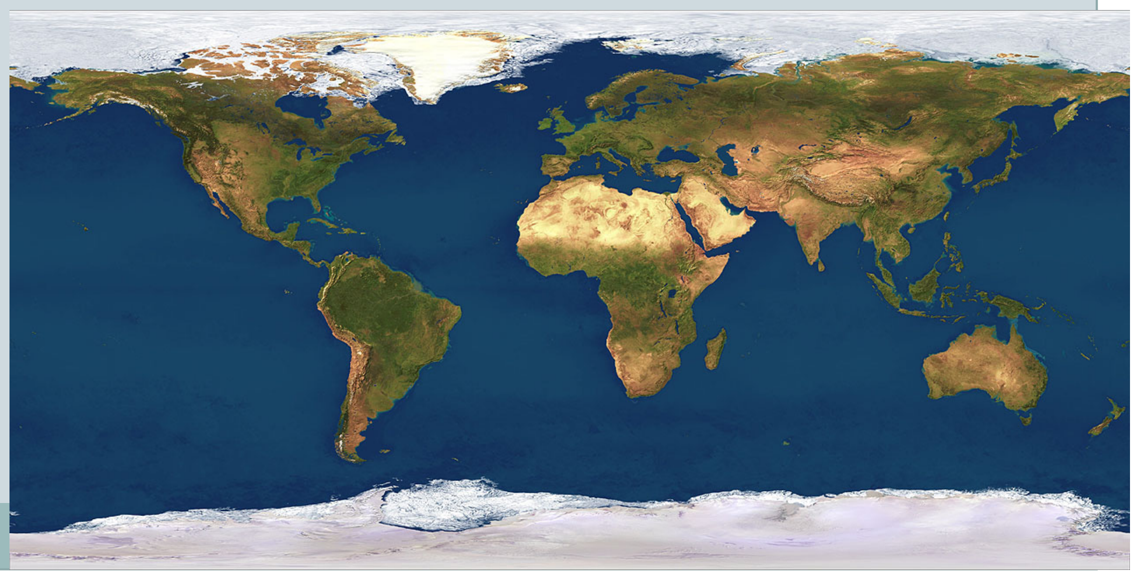
(Remember poles are exaggerated in Mercator projections like this)

# Albedo of Surfaces

- Albedos of different surfaces/clouds:




Surface reflects relatively small percentage of TOA solar radiation (~5%), but albedo is very important for local climate



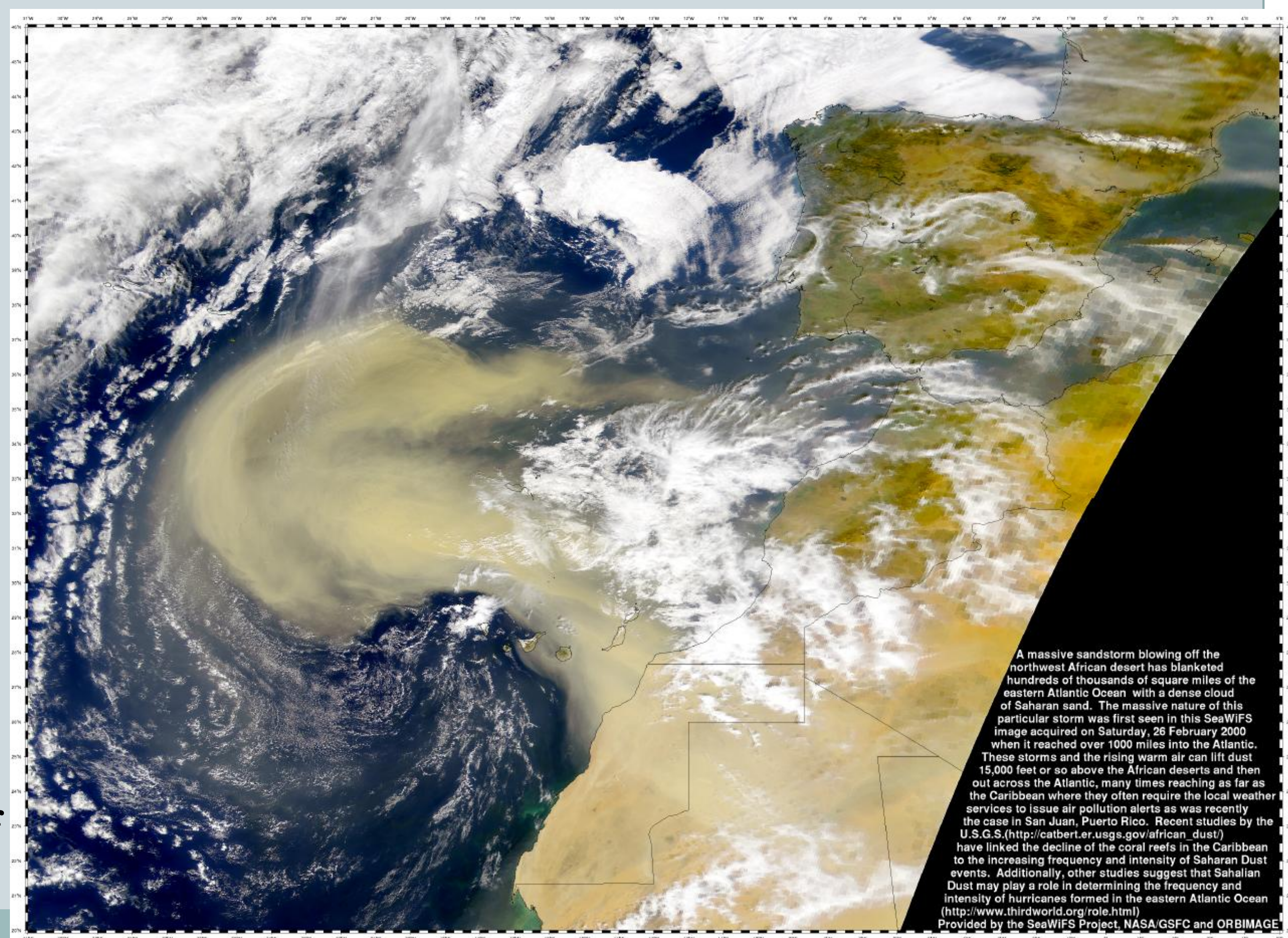
# Aerosols

- Atmospheric reflection is partially due to air molecules
- ***Aerosols*** (fine particles suspended in air) also make a large contribution to atmospheric reflection
  - Dust (e.g., from the Sahara)
  - Sea salt
  - Sulfur dioxide (from volcanoes, coal burning)
  - Soot
  - And others

# Dust

- Saharan dust transported across Atlantic:

Dust also absorbs solar in addition to reflecting (slightly different climate impacts)




Dust can be anthropogenic: Desertification/land use changes contribute ~30% of current dust levels

# Volcano Effects on Climate

- Volcanoes can have large climate impact
  - Esp. if they get material into stratosphere & have sulfates

Mount Pinatubo, Philippines, erupted June 1991, resulted in 0.5 C global temperature decrease

Volcanic climate impacts are through dust or aerosols:

Direct heating of atmosphere by volcanoes is small.

$CO_2$ emission by volcanoes is <1% of anthropogenic emission.

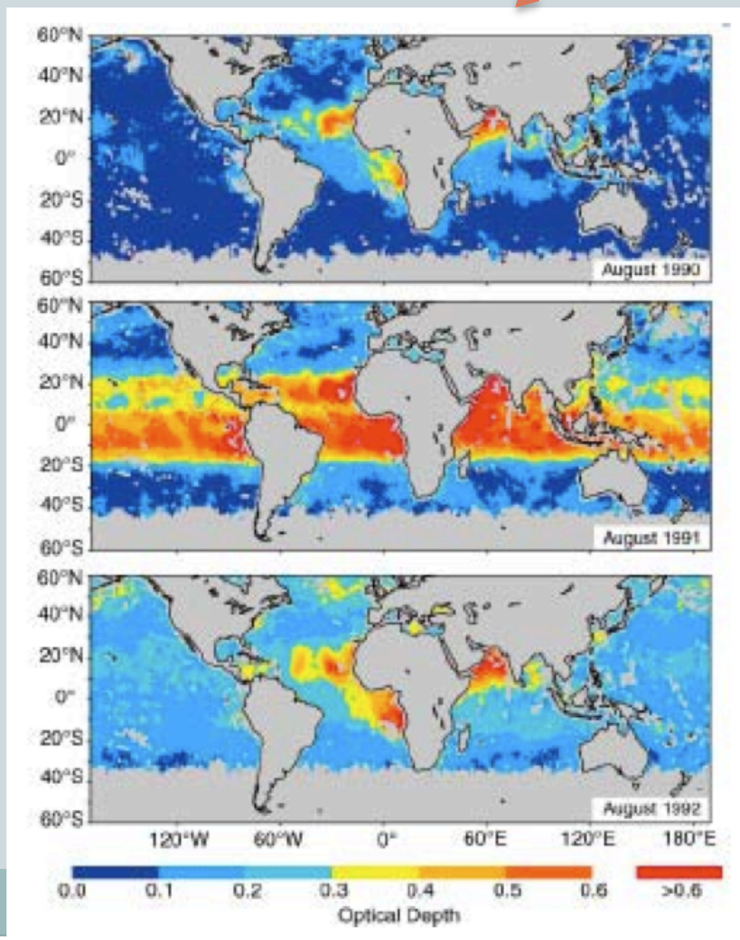
# Pinatubo Eruption Impacts

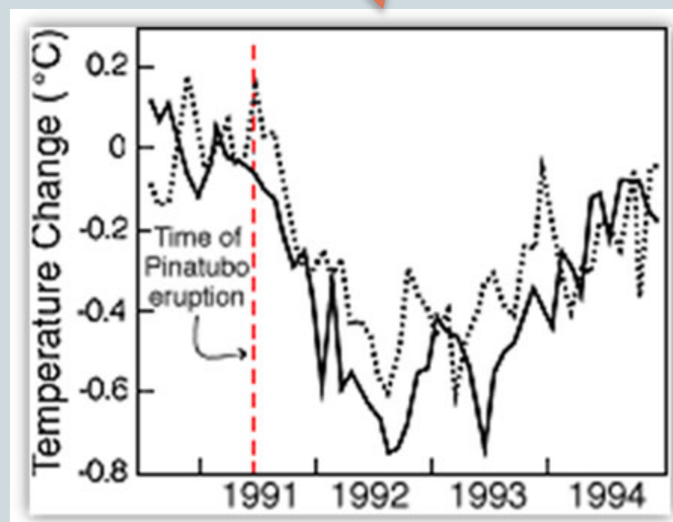
- Large increase in aerosols, decrease in temperature

Before →

2 months after →

14 months after →



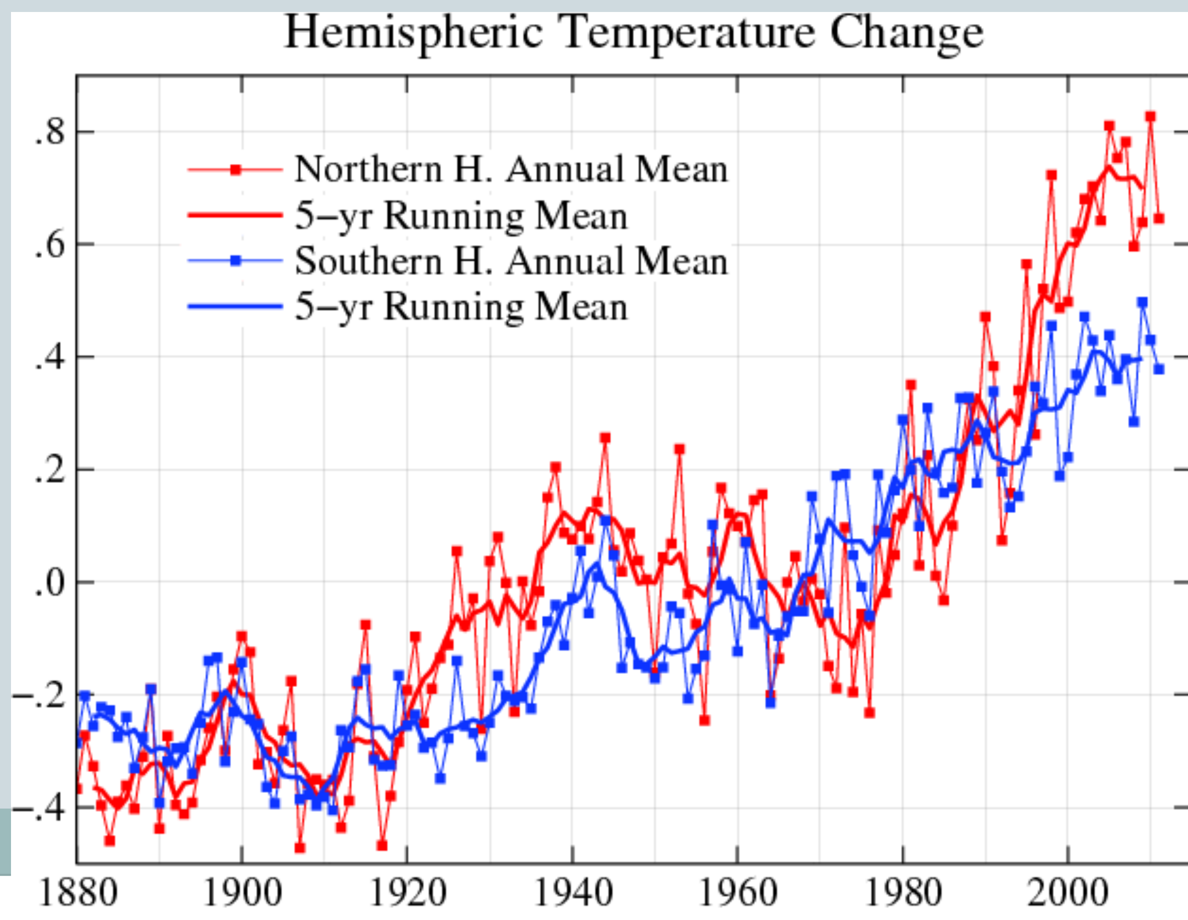

Observed (dashed) vs modeled (solid) temperature change (from Hansen et al 1996)

# “Global Dimming”

- Solar radiation reaching the Earth’s surface has declined by ~4% from 1961-1990
  - This has coexisted with large increases in the global temperature. Why?
- Increased aerosol concentrations partially to blame
  - Reflection changes from this is too small to explain the full effect though
- Cloud changes are important too: thicker and longer lived clouds
- Trend has reversed since 1990s (likely due to Clean Air Acts)

# NH vs SH Temperature Changes

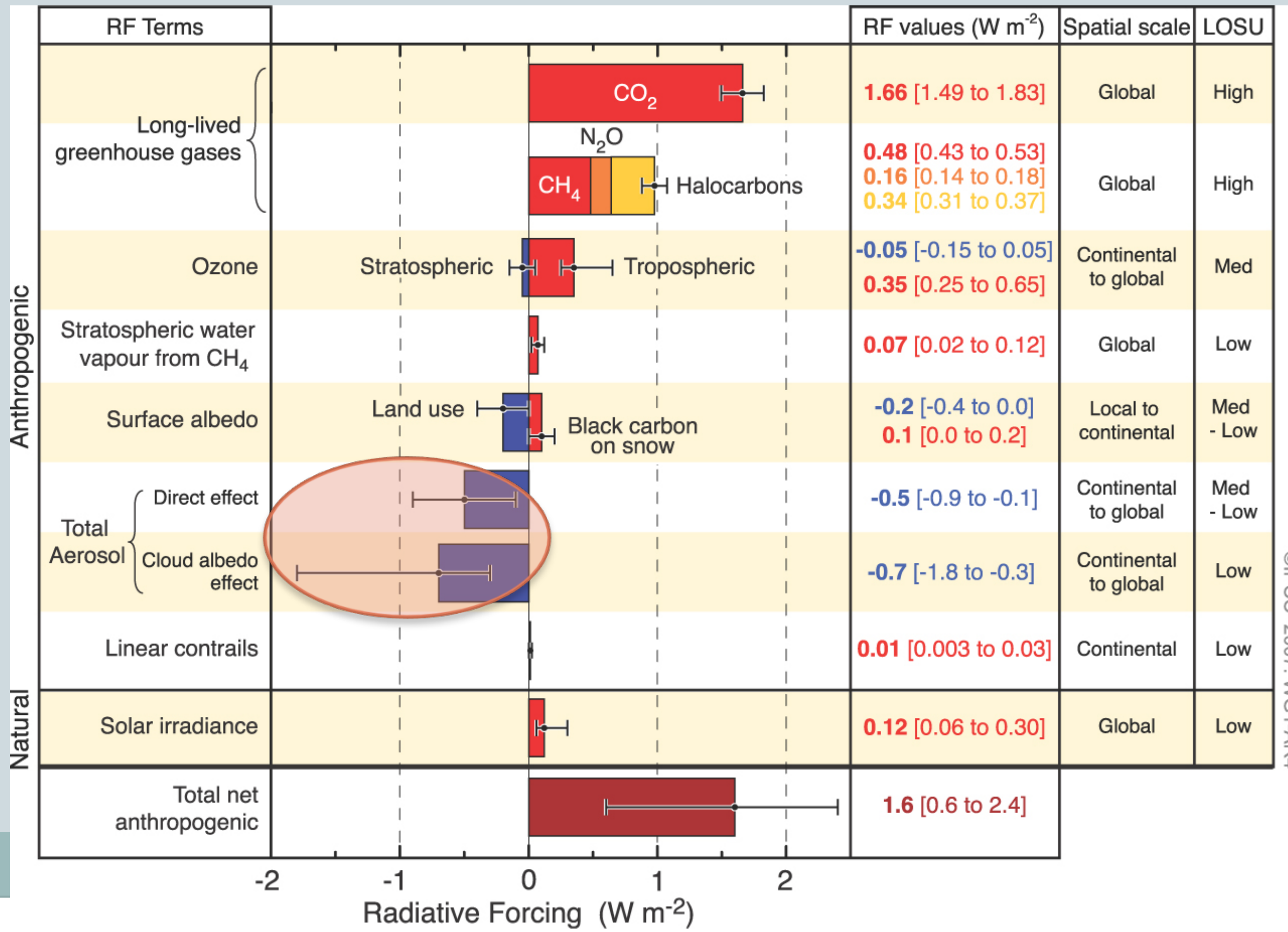
- NH vs SH warming difference due to aerosols/global dimming?



# Aerosols Impact on Climate

- Aerosols are **biggest uncertainty** in radiative forcing of climate change:

Radiative forcing of present climate, with uncertainties

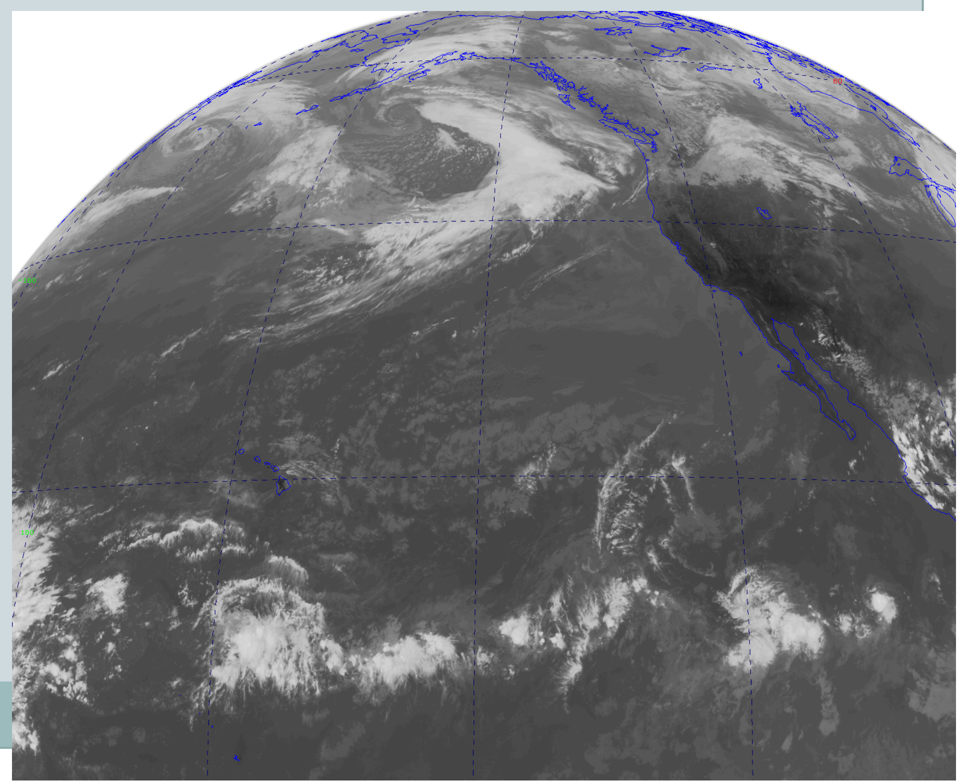



IPCC AR4 SPM

# Next Section: Earth Radiation

- In equilibrium, energy in = energy out
  - This is the "energy balance" equation
- The Earth loses energy only through **longwave radiation**
  - The Earth's surface radiates away lots of longwave radiation
  - Is this able to make it out to space easily?

Infrared satellite image →

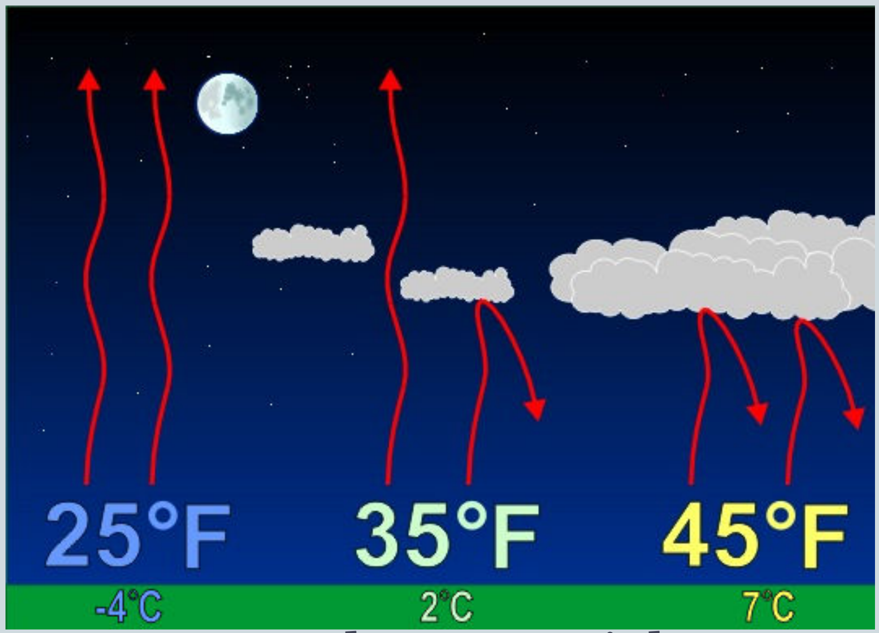


# Greenhouse Effect

- The surface emits **390** W/m² of longwave radiation, but only **40** W/m² makes it directly out to space
- The rest is trapped by greenhouse gases and clouds!

# The Greenhouse Effect

- Greenhouse effect is intuitive if you pay attention to the weather!
  - **Cloudy nights** cool less quickly




  - In the **desert**, temperatures plunge at night!
    - No clouds & little water vapor in the desert: little greenhouse effect

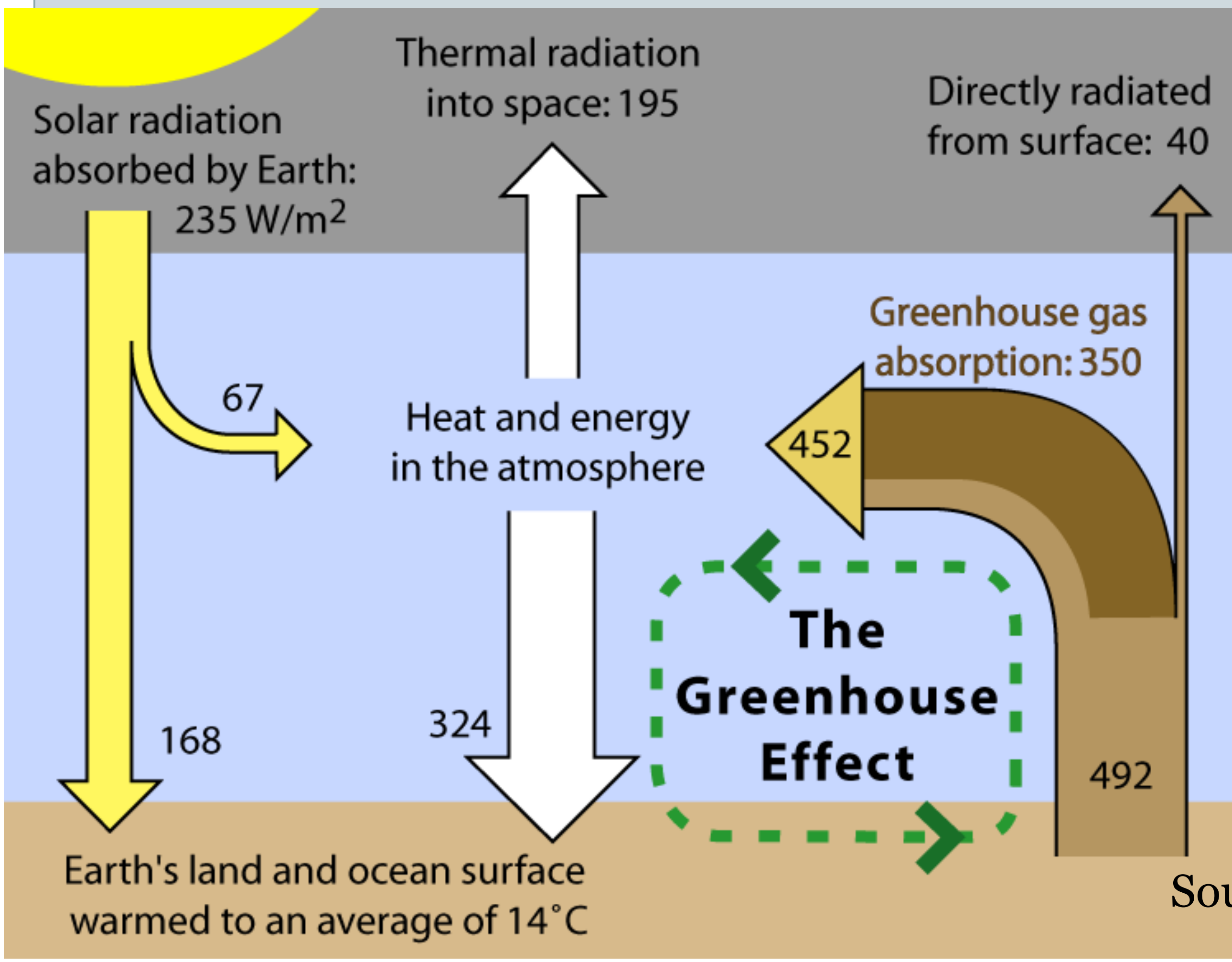
# The Greenhouse Effect

- Without the greenhouse effect, surface temperatures would be -18$^o$ C
- Book also has example of atmosphere that's purely opaque to longwave and transmitting to shortwave

- Result: surface temperature =303 K
  - Too hot, but closer to this limit than no greenhouse effect…

# Atmospheric Energy Budget

- Surface is heated more by **longwave** than shortwave!




Source: Global Warming Art

# Greenhouse Gas Absorption

- For a gas to absorb a particular wavelength (and energy), there must be an allowed transition with the same energy
  - Rotational modes
  - Vibrational modes
  - Photodissociation (e.g., ozone breaking down into oxygen)
- No transitions => radiation makes it through air without being absorbed

# Greenhouse Gases

- Diatomic molecules ($N_2$, $O_2$, etc) and monatomic molecules don't interact with longwave
- Greenhouse gases are all polyatomic: $H_2O$, $CO_2$, $CH_4$, $O_3$, $N_2O$
  - Vibration mode is the transition that absorbs the infrared
- Absorption tends to be at a single wavelength ("line")
  - Lines are then broadened by various processes

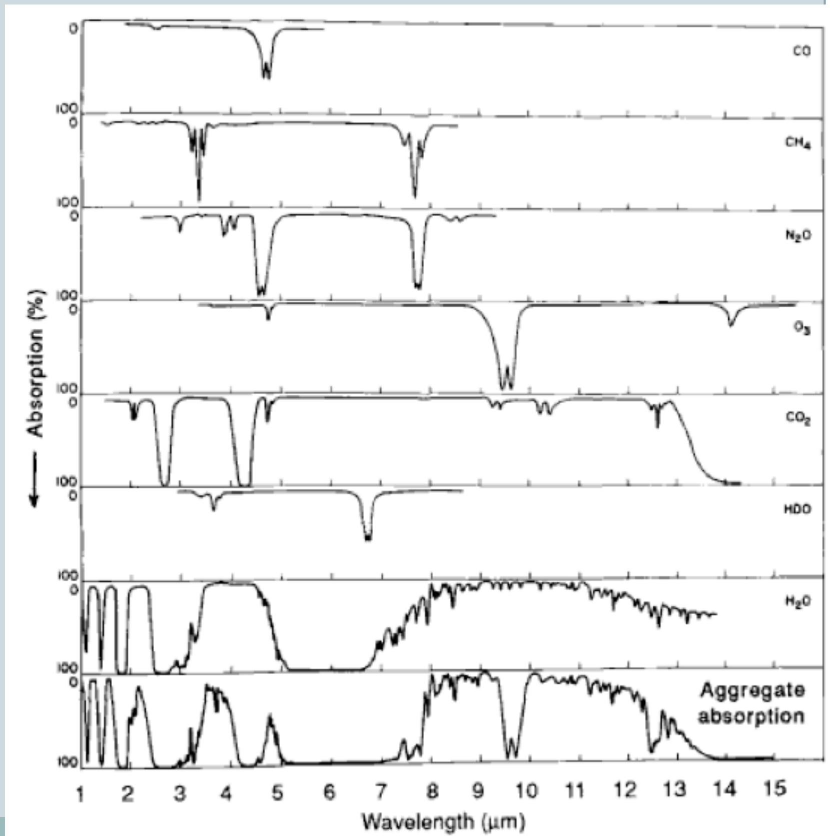
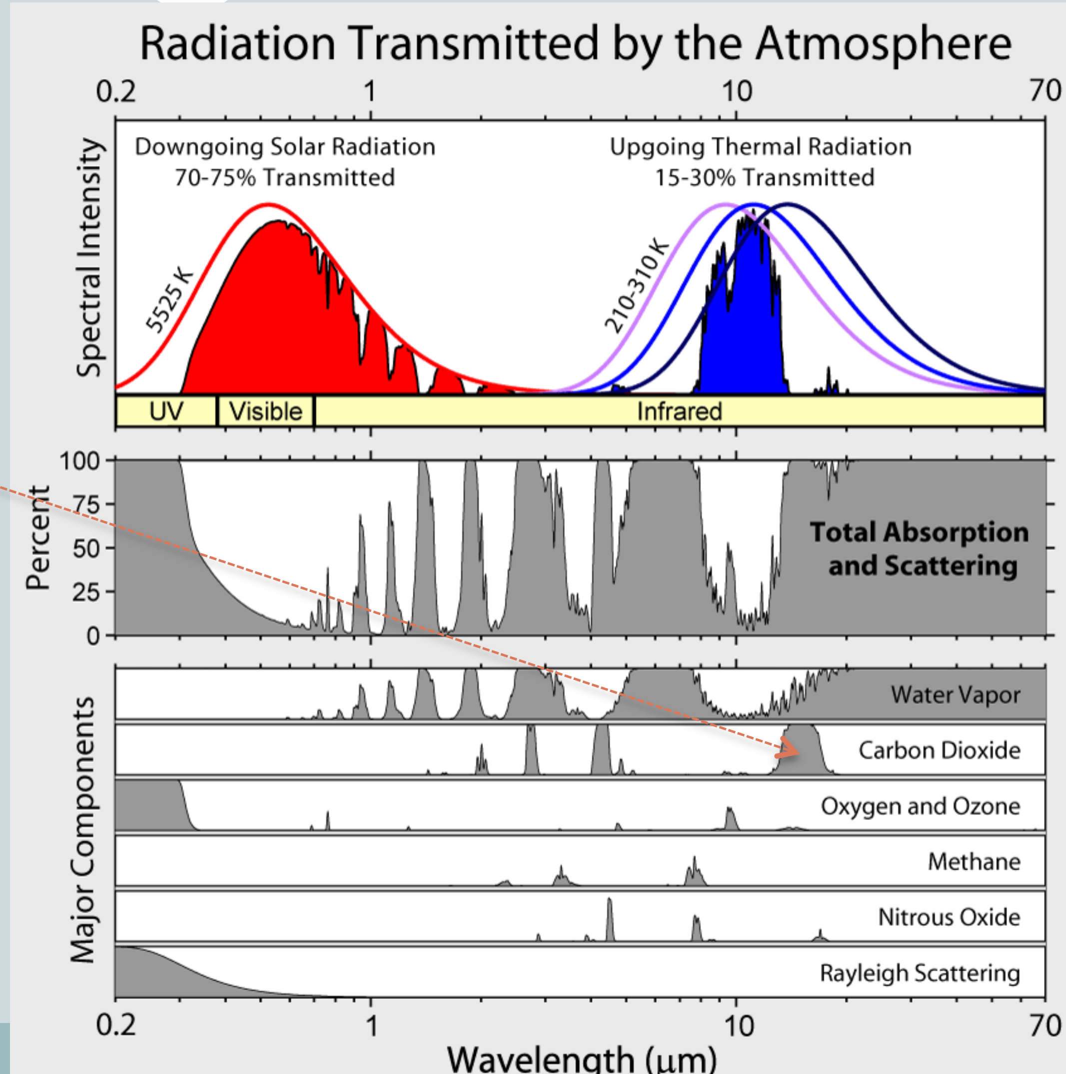



**Fig. 3.4** Infrared absorption spectra for various atmospheric gases. [From Valley (1965). Used with permission from McGraw-Hill, Inc.]

# Absorption of Longwave Radiation

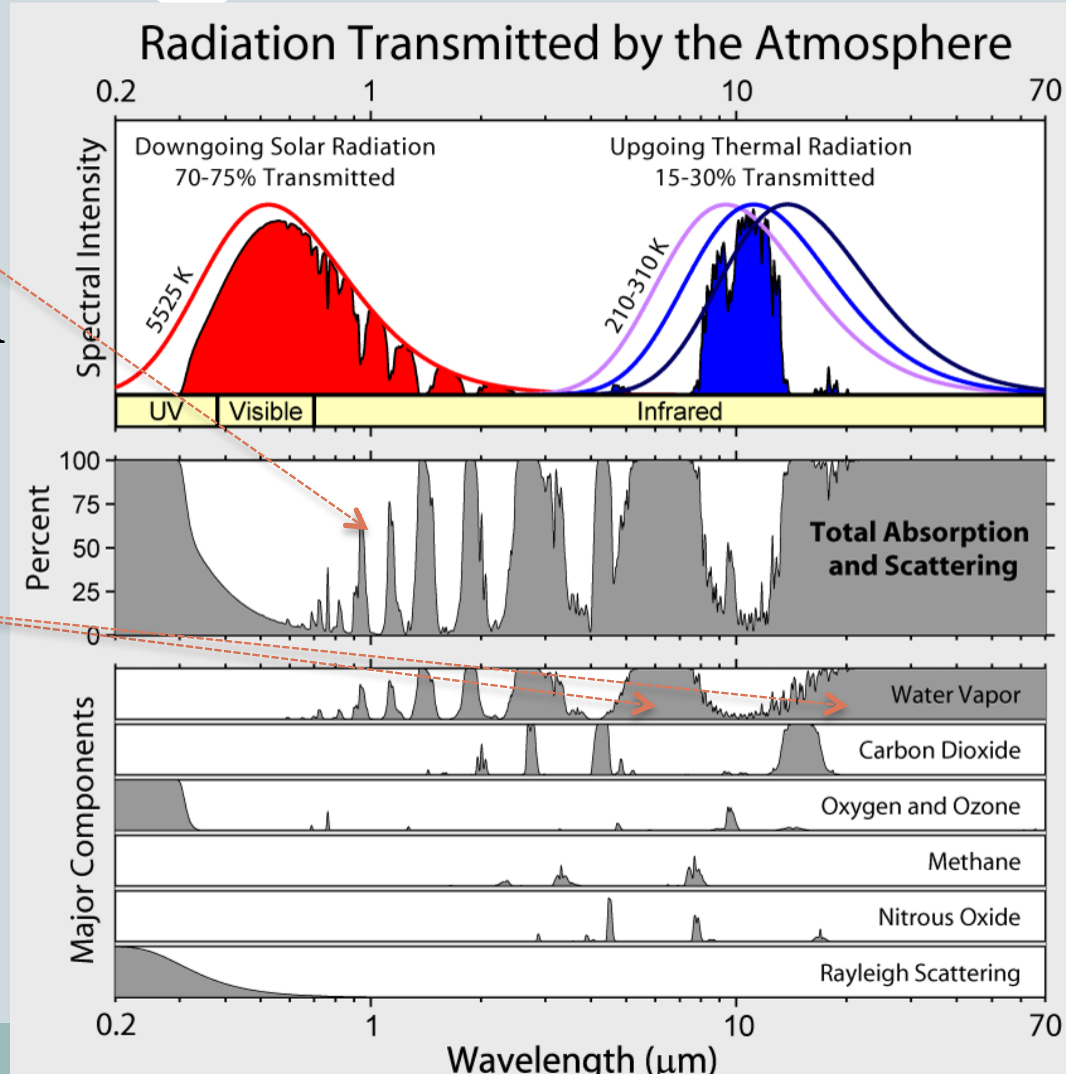
- LW absorption on the right
- Note $CO_2$ band is **saturated** in the middle
  - **Myth**: saturation means $CO_2$ can't cause global warming
  - Lines still can get broader




Source: Global Warming Art

# Absorption of Longwave Radiation

- **Water vapor** does most of the absorption of shortwave radiation
- Also the most important greenhouse gas!




Source: Global Warming Art

# Another Way to Think about Greenhouse Effect

- The atmosphere gets thinner as you go up
- So eventually greenhouse gases become less prevalent and radiation can escape more easily
- But it's colder up there too!  So emission is less

- Thinking about the vertical temperature profile is important for the greenhouse effect – next topic!

# Radiation Summary

- Solar variability is small (< 0.1%)
- 30% of solar radiation is reflected back to space
  - 20% by clouds, 5% by atmosphere, 5% by surface
- Greenhouse effect is big on Earth!
  - Very hard for radiation to escape from space
  - "Back radiation" (longwave down at the surface from the greenhouse effect) is almost twice as big as solar!
  - Greenhouse effect causes planet to be around $33^{o}$ C warmer