Climate Dynamics (PCC 587): Radiation

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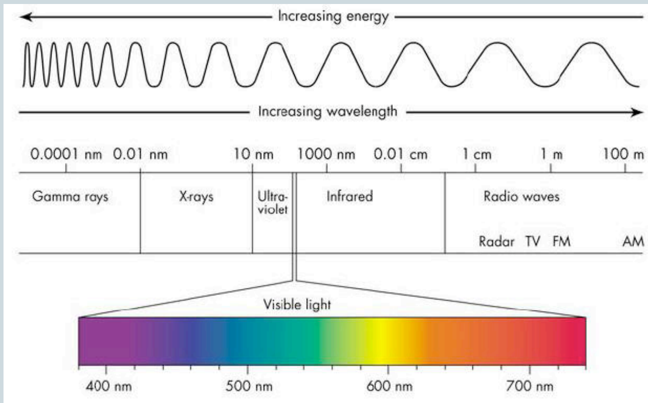
DAY 2: 10-6-09

Last time…

- Radiatively active gases are very small fraction of atmospheric mass
- Compressibility of air leads to decrease of temperature with altitude in troposphere
  - Lower pressure -> colder
  - Seawater is essentially not compressible
    - Even though pressure *doubles* when you go down 10 meters in the ocean, temperature/density of seawater doesn't change due to this
- Stratosphere is there due to ozone layer

Today: Radiative Transfer

- Radiation = light
  - Visible or otherwise…



Shorter wavelengths => more energetic

Today: Radiative Transfer

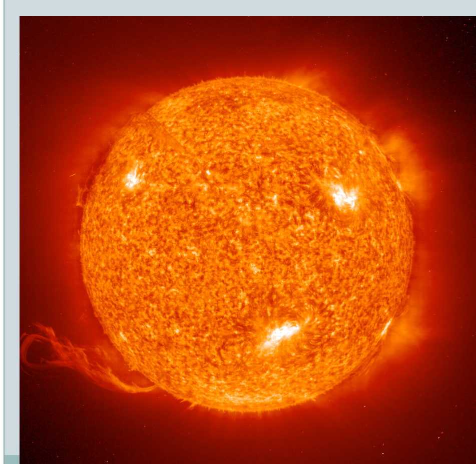
- The sun
  - Characteristics of radiation reaching the top of the atmosphere
- Solar radiation interacting with the Earth
  - Reflection, absorption
  - Effects of clouds, aerosols, volcanoes, etc
- How the Earth radiates away heat
  - Effect of CO2, water vapor, etc
  - Greenhouse effect
- All the discussion today will be globally averaged
  - Next class we'll start talking about tropics vs poles, etc…

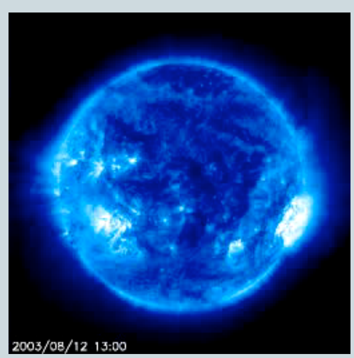
Radiative Transfer in Climate Models

- Clear sky radiative transfer is essentially a solved problem
  - We know exactly how to do this as accurately as we want
- However, it's very expensive computationally
  - 50% of computing time of atmospheric global climate models (GCMs) is used on radiative transfer
  - Some differences among climate models has been shown to be due to radiative transfer (presumably the approximations made to make them computationally feasible)
- Radiative transfer of clouds, aerosols, and sea ice is more difficult

Solar Radiation

- Driver of everything in the climate system!

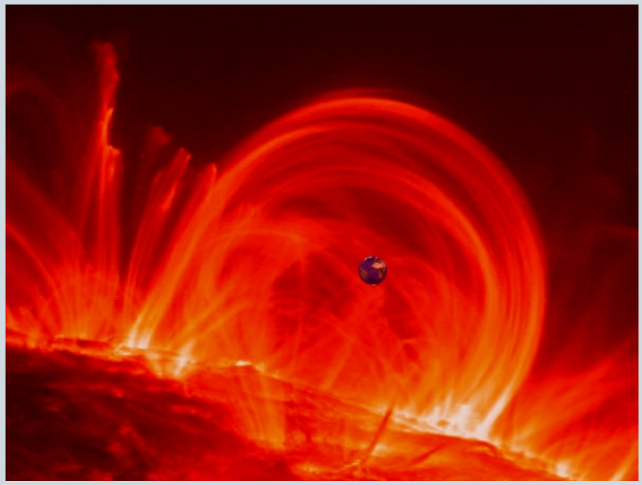




We Are Small!

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
σ = Stefan-Boltzmann constant = 5.67x10^-8 W/m^2/K^4

Key equation!!!

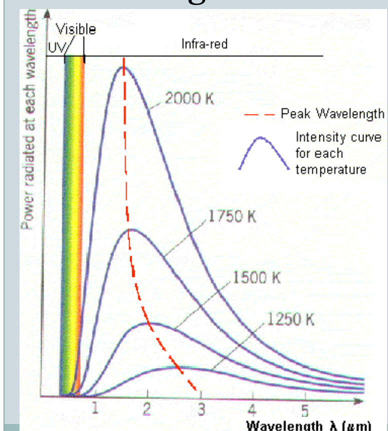
Wien's Displacement Law:

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

T = temperature
λ_{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:



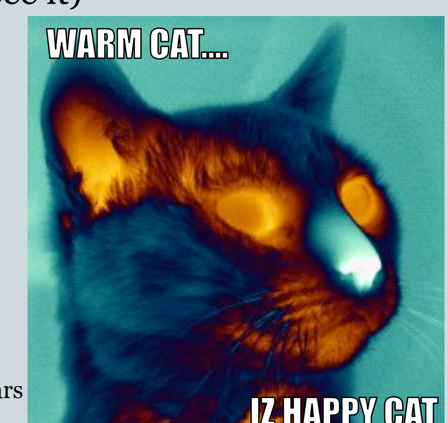
Stefan-Boltzmann Law tells you the integral under the blue curves (total emission over all wavelengths)

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

Spectrum of the Sun's Radiation

- Solar radiation is mostly in the visible bands

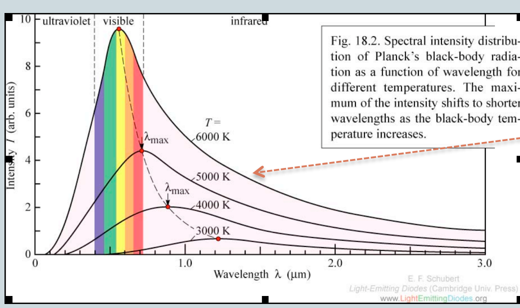


Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

Top curve is close to what the sun emits

- Also significant UV and infrared emission by the sun

Solar Radiation

- 5780 K blackbody is good approximation to solar radiation

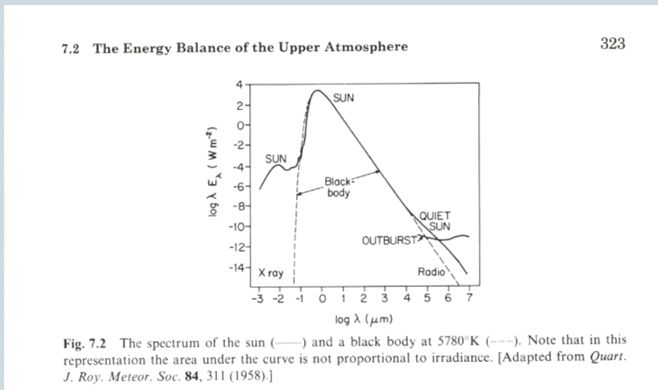
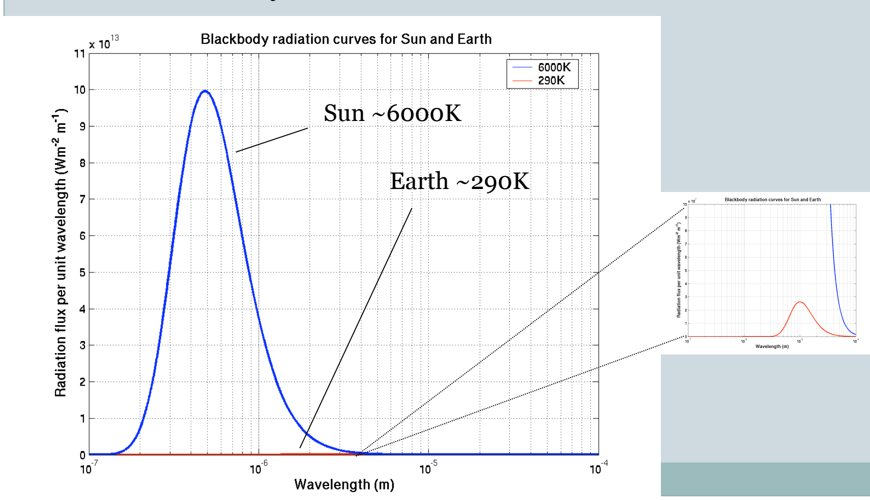


Fig. 7.2 The spectrum of the sun (——) and a black body at 5780°K (– – –). Note that in this representation the area under the curve is not proportional to irradiance. [Adapted from *Quart. J. Roy. Meteor. Soc.* **84**, 311 (1958).]

Houghton 2002

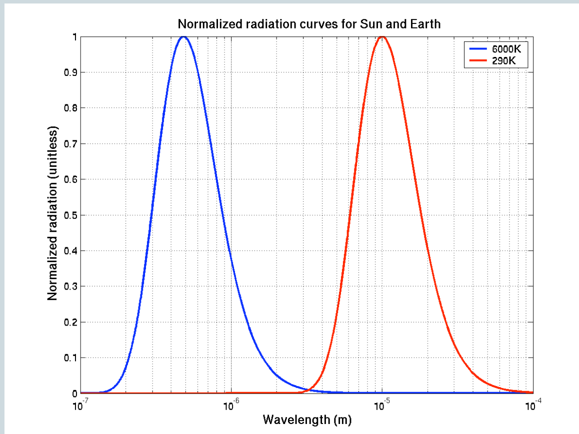
Solar Radiation

- Sun emits way more radiation than the Earth!



Solar vs Terrestrial Radiation

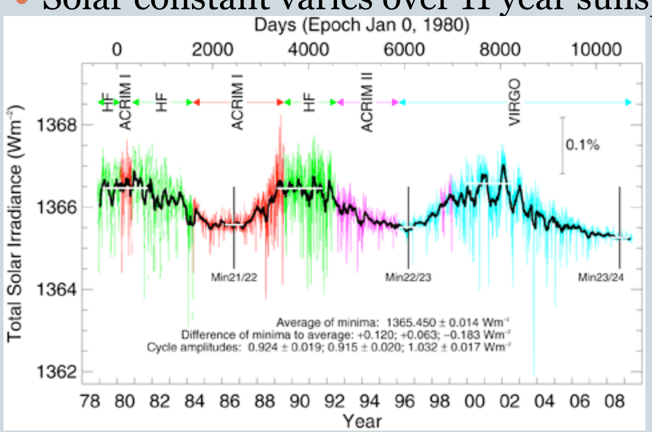
- Normalize the curves so maximum intensities are equal:



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

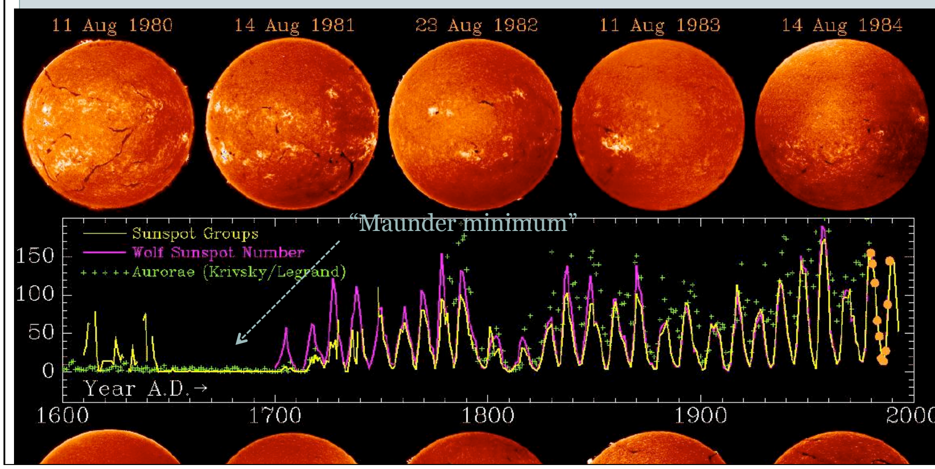
Affects global temperatures by 0.2 K? (research of KK Tung, Applied Math)

We are in a prolonged minimum in solar activity

- Note high frequency variability as well

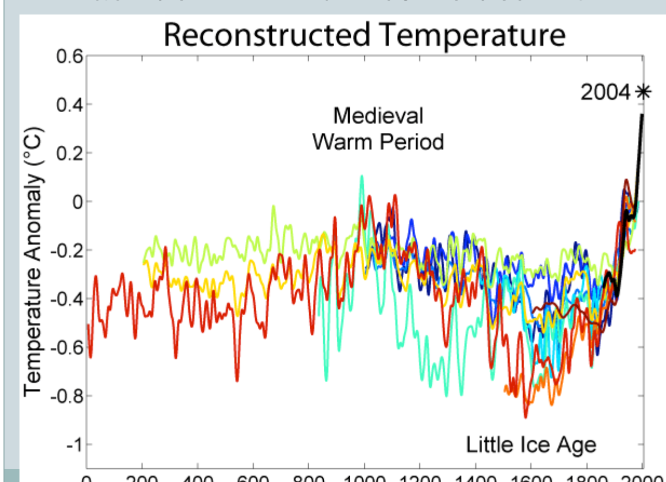
Sunspot Cycles over Time

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



Sunspot Cycles over Time

- Maunder minimum coincides with "Little Ice Age":

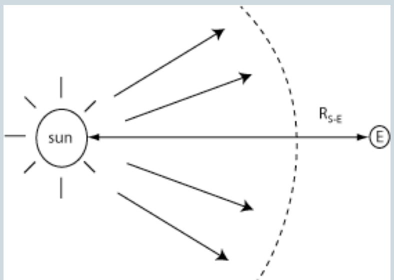


There was also enhanced volcanic activity at this time

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

For average radiation on Earth, have to take account that 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?
- 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 (25% by atmosphere, 5% by surface)

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 => light makes it through air without being absorbed

Solar Radiation in the Earth's Atmosphere

- Absorption (shaded):
  - Mostly in infrared band (vibrational transitions of water vapor)
  - Clouds, CO2 absorb some too
  - Ozone photodissociation important for absorbing UV (this is most of the 3% absorbed in stratosphere)

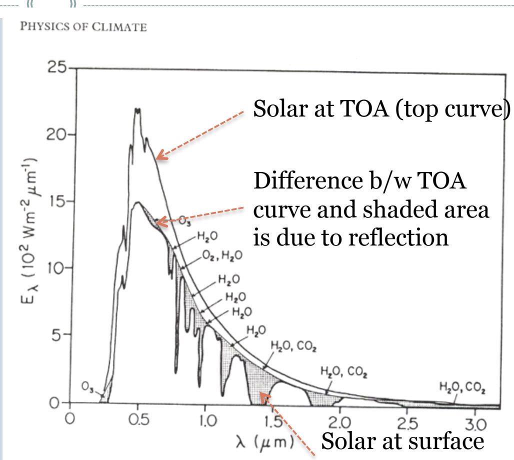


FIGURE 6.1. Spectral distribution of solar irradiation at the top of the atmosphere and at sea level for average atmospheric conditions for the sun at zenith. The shaded areas represent absorption by various atmospheric gases. The unshaded area between the two curves represents the portion of the solar energy backscattered by the air, water vapor, dust, and aerosols and reflected by clouds. For the curve at the top of the atmosphere the integral $\int_0^\infty E_\lambda \, d\lambda \simeq 1360$ W m^{-2} represents the solar constant (adapted from Gast, 1965).

Absorption of Solar Radiation

absorption

100% ——

0% ——

Left side shows how solar radiation is absorbed

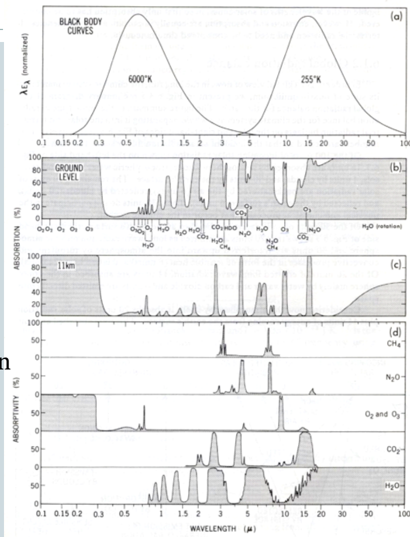


FIGURE 6.2. Black body curves for the solar radiation (assumed to have a temperature of 6000 K) and the terrestrial radiation (assumed to have a temperature of 255 K) (a); absorption spectra for the entire vertical extent of the atmosphere (b) and for the portion of the atmosphere above 11 km (c) after Goody (1964); and absorption spectra for the various atmospheric gases between the top of the atmosphere and the earth's surface (d) after Howard *et al.* (1955) [updated with data from Fels and Schwarzkopf (1988, personal communication) between 10 and 100 μm].

Entire atmosphere

> 11 km

— CH_4

— N_2O

— O_2,O_3

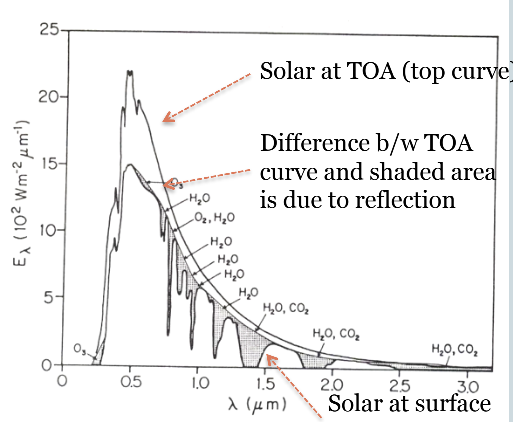
— CO_2

— H_2O

Solar Radiation in the Earth's Atmosphere

- Reflection (30% of TOA):
  - 20% by clouds
  - 5% by atmosphere
  - 5% by surface
- For gases/droplets/ particles, reflection occurs when size is similar to wavelength of light or larger

PHYSICS OF CLIMATE



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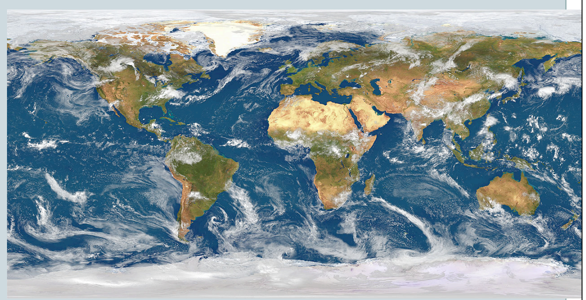
Albedo

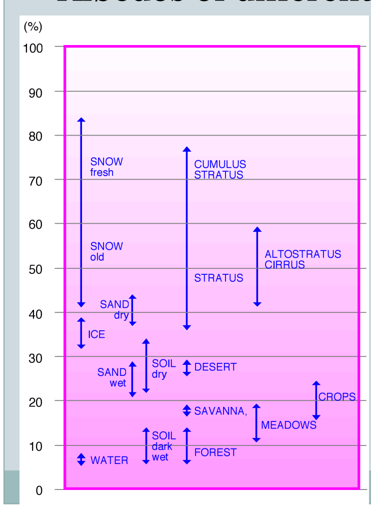
- Albedo: reflectivity of a surface
  - Black = 0, white = 1
- Clouds are largest contribution to Earth albedo
  - Cloud albedo depends primarily on thickness (0.2-0.7)
- Ocean is very dark (<0.1)
- Desert ~ 0.3, forest ~0.15, snow ~ 0.4-0.9



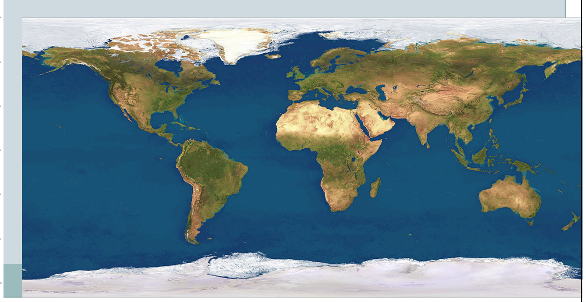
(Remember poles are exaggerated in Mercator projections like this)

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



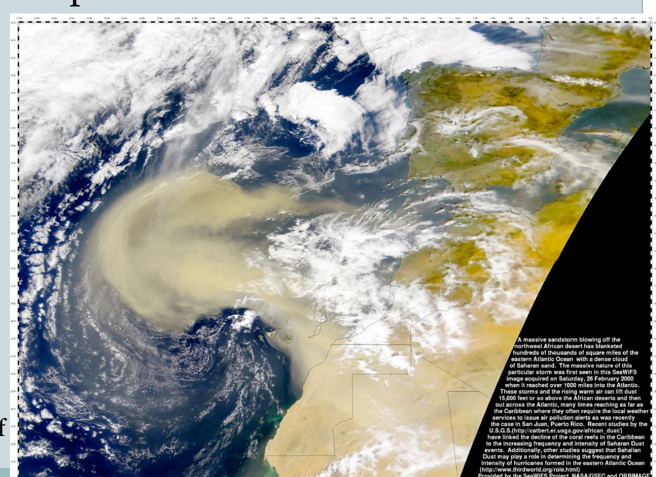
Aerosols

- 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:

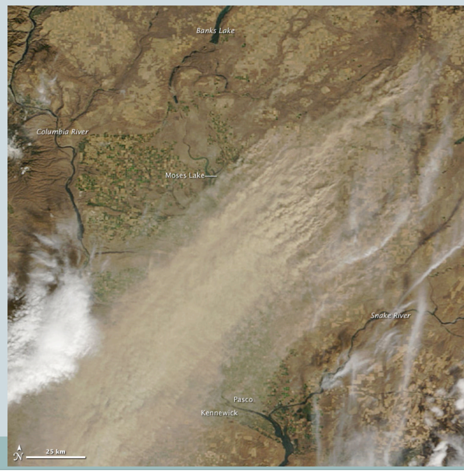
Dust also absorbs solar in addition to reflecting (slightly different climate impacts)



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

Dust Storm

- Eastern Washington dust storm on Sunday:



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.

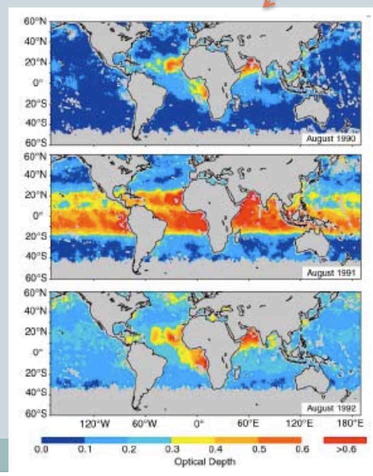
Pinatubo Eruption Impacts

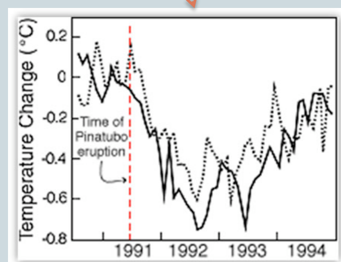
- Large increase in aerosols, decrease in temperature

Before →

2 months after →

14 months after →





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

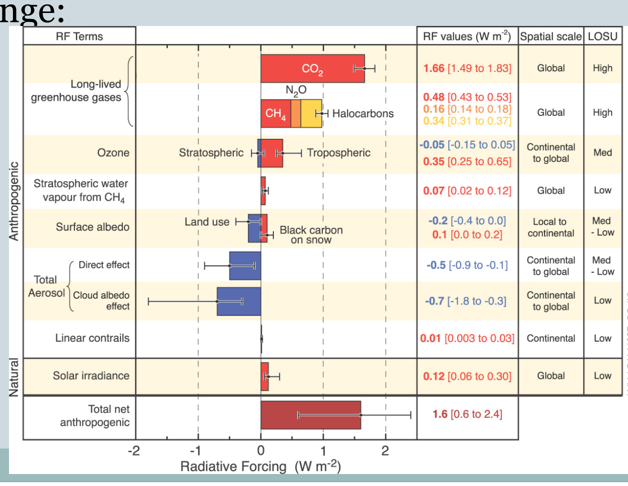
"Global Dimming"

- 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 somewhat reduced since 1990s (due to Clean Air Act?)

Aerosols Impact on Climate

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

Radiative forcing of present climate, with uncertainties



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Next Section: Earth Radiation

- In equilibrium, energy in = energy out
- The Earth loses energy only through longwave radiation
- Currently, outgoing radiation is less than incoming solar, and the Earth is warming
  - This imbalance is relatively small though (~1 W/m2): it's still extremely useful to consider the equilibrium situation

Estimate of Earth's Temp w/o Greenhouse

- Insolation: 30% is reflected and 70% is absorbed:
  - Net solar radiation at TOA (downward minus upward) = 0.7*341 W/m^2 ~ 240 W/m^2
- In equilibrium, all of this must leave the Earth via longwave radiation (otherwise the Earth would heat up)
  - Let's calculate this assuming no atmosphere: E = sigma T^4 ......or....... T = (E/sigma)^(1/4)

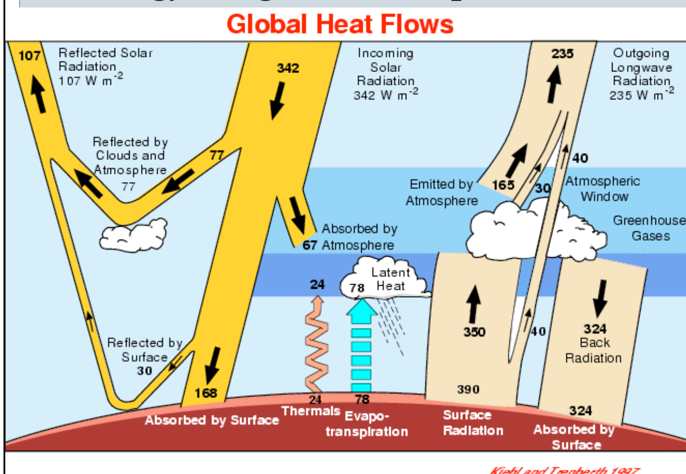
Get T = 255 K = -18 C = 0 F ← **Really cold!!** (it's actually 288 K)

The Greenhouse Effect

- We just showed w/o the greenhouse effect, surface temperatures would be 0 F
- 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

- Energy budget of atmosphere:

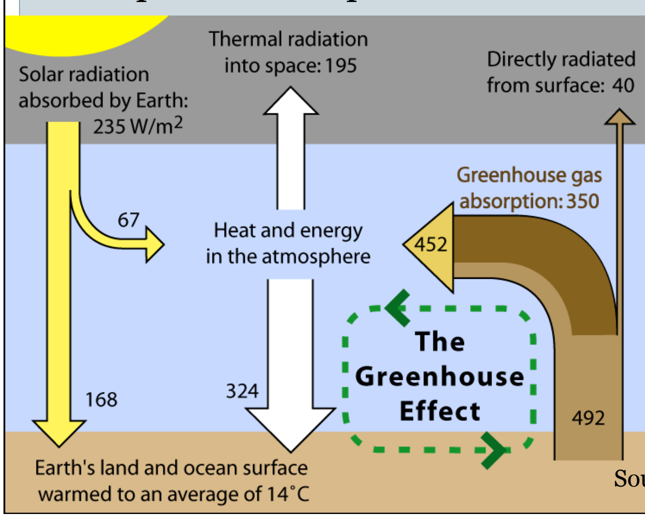


Note of 390 W/m2 emitted by surface, only 40 W/m2 makes it all the way out

We're closer to the fully absorbing limit than to the no atmosphere limit…

Atmospheric Energy Budget

- Simplification of previous slide:



Source: Global Warming Art

Greenhouse Effect

- Greenhouse effect is also key in limiting diurnal temperature change
  - We'd have much colder nights w/o greenhouse effect
  - Cloudy nights clear much more slowly
- Desert climates also cool quickly
  - Hot days, cool nights
- High humidities were key to the record-breaking heat here at the end of July (high of 103, low of 71)

Greenhouse Gases

- Diatomic molecules (N_2, O_2, etc) and monatomic molecules don't have dipole moment when vibrating
- H_2O, CO_2, NH_4, O_3, N_2O are all greenhouse gases
  - Note they're all polyatomic
- Absorption tends to be at a single wavelength ("line")
  - Lines are then broadened by various processes

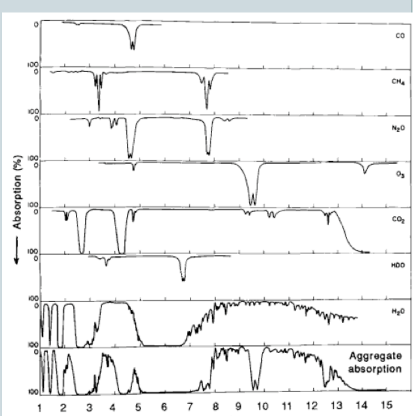
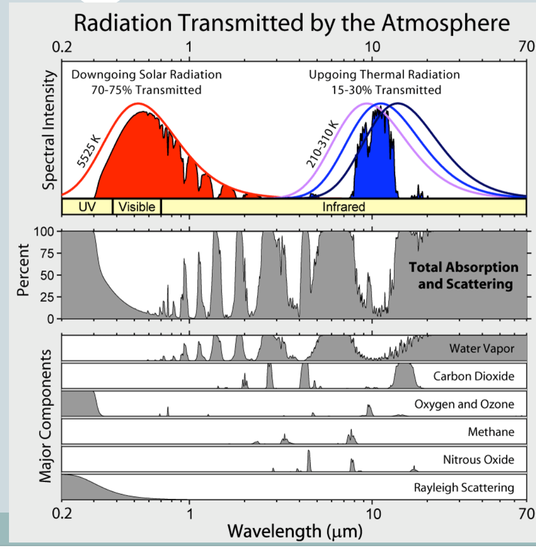


Fig. 3.4 Infrared absorption spectra for various atmospheric gases. [From Valley (1965). Used with permission from McGraw-Hill, Inc.]

Absorption of Longwave Radiation

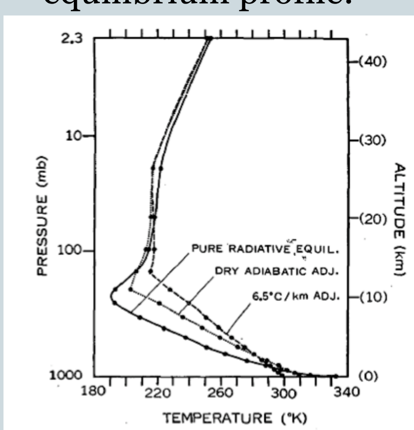
- LW absorption on the right



Source: Global Warming Art

Radiative Equilibrium

- With a radiative model, can calculate radiative equilibrium profile:



Get profiles that are convectively unstable: too hot below, too cold above

Can correct by setting a lapse rate for convection

Global Warming and Rising Emission Levels

- Consider the climate coming into equilibrium with a doubling of CO_2
  - OLR has to get to same value in equilibrium (b/c solar is same)
- Emission level rises
  - More absorber, so atmosphere is thicker to LW to higher up
- Can calculate surface temperature change from the lapse rate and emission level

Next time: Latitudinal Profiles!

- Hotter tropics, colder poles
- How atmospheric and oceanic circulations transport heat poleward
- An intro to the first project