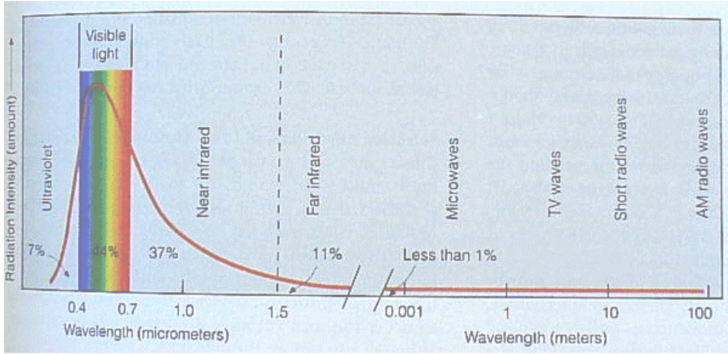
Radiation and the Planetary Energy Balance

- Electromagnetic Radiation
- Solar radiation warms the planet
- Conversion of solar energy at the surface
- Absorption and emission by the atmosphere
- The greenhouse effect
- Planetary energy balance

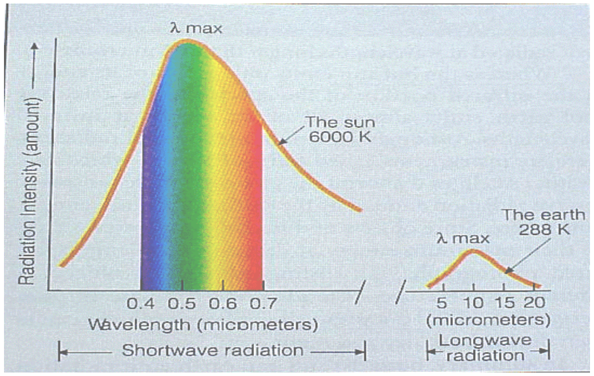
Electromagnetic Radiation

- Oscillating electric and magnetic fields propagate through space
- Virtually all energy exchange between the Earth and the rest of the Universe is by electromagnetic radiation
- Most of what we perceive as temperature is also due to our radiative environment
- May be described as waves or as particles (photons)
- **High energy photons = short waves; lower energy photons = longer waves**

Electromagnetic Spectrum of the Sun



Spectrum of the sun compared with that of the earth



Blackbodies and Graybodies

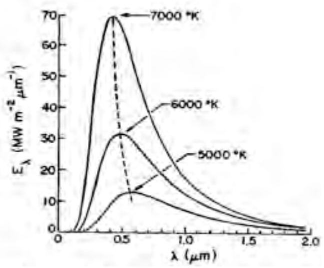
- A blackbody is a hypothetical object that absorbs all of the radiation that strikes it. It also emits radiation at a maximum rate for its given temperature.
  - Does not have to be black!
- A graybody absorbs radiation equally at all wavelengths, but at a certain fraction (absorptivity, emissivity) of the blackbody rate
- The energy emission rate is given by
  - Planck's law (wavelength dependent emission)
  - Stefan Boltzmann law (total energy)
  - Wien's law (peak emission wavelength)

Blackbody Radiation

Planck's Law

$$E_\lambda = \frac{c_1}{\lambda^5[\exp(c_2/\lambda T) - 1]}$$

$$\simeq c_1 \lambda^{-5} \exp(-c_2/\lambda T)$$



- Planck's Law describes the rate of energy output of a blackbody as a function of wavelength
- Emission is a very sensitive function of wavelength
- Total emission is a strong function of temperature

Total Blackbody Emission

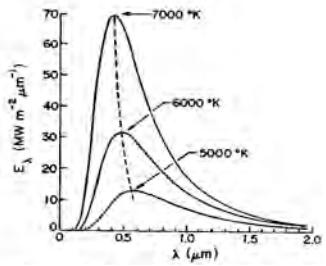
- Integrating Planck's Law across all wavelengths, and all directions, we obtain an expression for the total rate of emission of radiant energy from a blackbody:

$$E^* = \sigma T^4$$

- This is known as the Stefan-Boltzmann Law, and the constant s is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).
- Stefan-Boltzmann says that total emission depends really strongly on temperature!
- This is strictly true only for a blackbody. For a **gray body**, $E = \varepsilon E^*$, where ε is called the emissivity.
- In general, the emissivity depends on wavelength just as the absorptivity does, for the same reasons: $\varepsilon_\lambda = E_\lambda / E^*_\lambda$

Red is Cool, Blue is Hot

Take the derivative of the Planck function, set to zero, and solve for wavelength of maximum emission



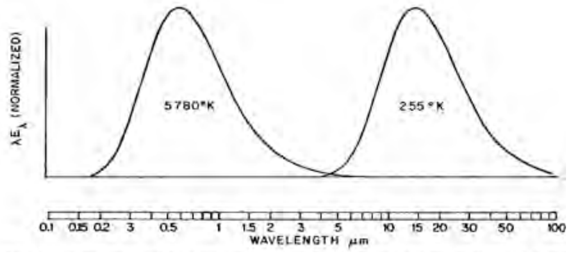
Wien's Displacement Law

$$\lambda_{max} = \frac{2897}{T}$$

(energy is concentrated at shorter wavelegths for hotter emitters)

Solar and Planetary Radiation

- Earth receives energy from the sun at many wavelengths, but most is visible or shorter
- Earth emits energy back to space at much longer (thermal) wavelengths
- Because temperatures of the Earth and Sun are so different, it's convenient to divide atmospheric radiation conveniently into solar and planetary

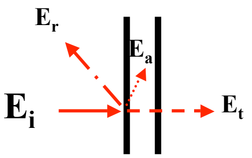


Ways to label radiation

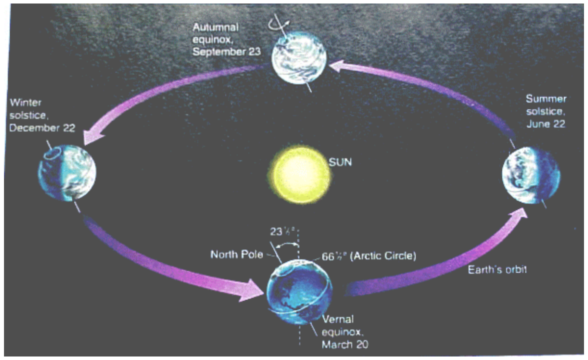
- By its source
  - Solar radiation - originating from the sun
  - Terrestrial radiation - originating from the earth
- By its name
  - ultra violet, visible, near infrared, infrared, microwave, etc….
- By its wavelength
  - short wave radiation $\lambda \leq 3$ micrometers
  - long wave radiation $\lambda > 3$ micrometers

Conservation of Energy

- Radiation incident upon a medium can be:
  - absorbed
  - reflected
  - transmitted
- $E_i = E_a + E_r + E_t$
- **Define**
  - reflectance $r = E_r/E_i$
  - absorptance $a = E_a/E_i$
  - transmittance $\tau = E_t/E_i$
- Conservation: $r + a + \tau = 1$

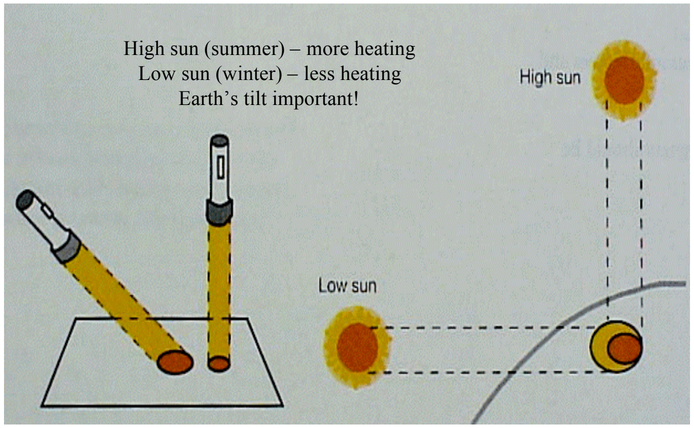


The Earth's Orbit Around the Sun

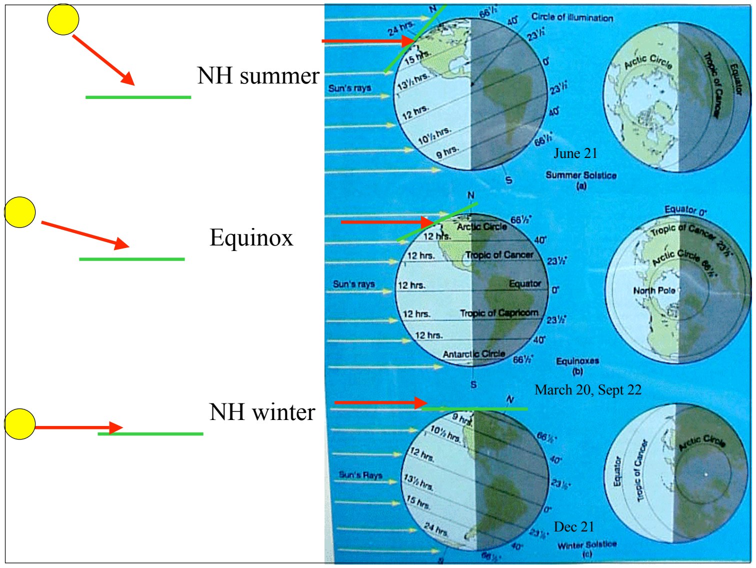


- Seasonally varying distance to sun has only a minor effect on seasonal temperature
- The earth's orbit around the sun leads to seasons because of the tilt of the Earth's axis

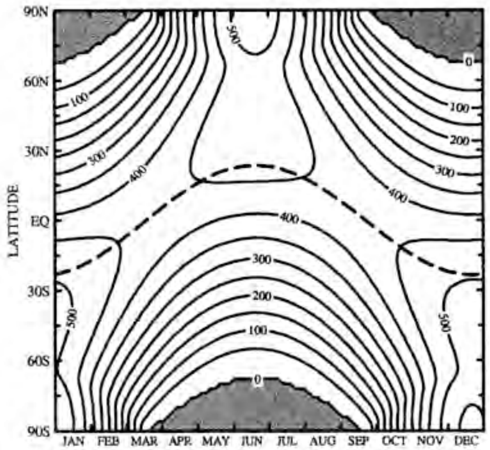
Smaller angle of incoming solar radiation: the same amount of energy is spread over a larger area



High sun (summer) – more heating
Low sun (winter) – less heating
Earth's tilt important!

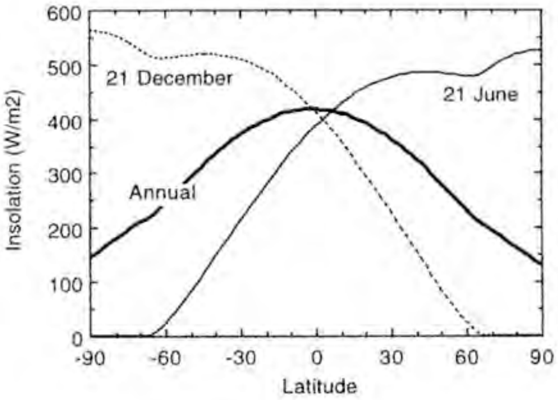


Daily Total Sunshine



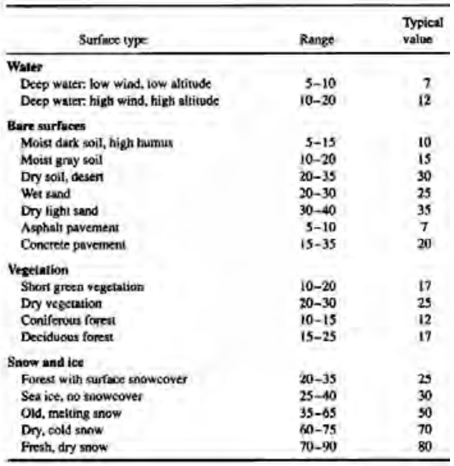
- 75° N in June gets more sun than the Equator
- N-S gradient very strong in winter, very weak in summer
- Very little tropical seasonality

Top-of-Atmosphere Daily Insolation
(zonal integral)



- Nearly flat in summer hemisphere
- Steep gradient from summer tropics to winter pole

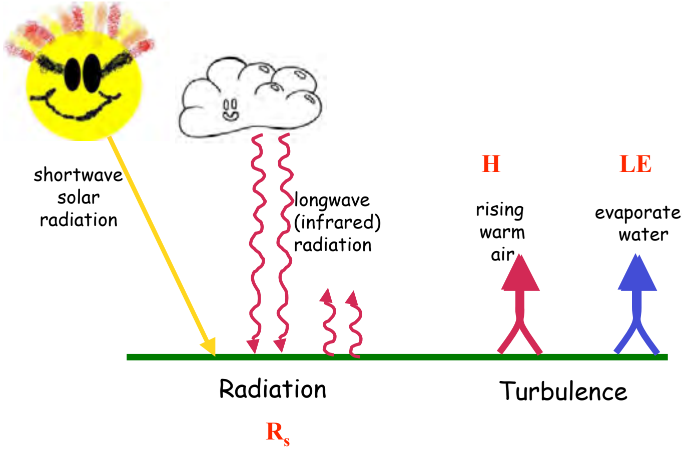
Surface Albedos (percent)



Surface type	Range	Typical value
Water		
Deep water: low wind, low altitude	5–10	7
Deep water: high wind, high altitude	10–20	12
Bare surfaces		
Moist dark soil, high humus	5–15	10
Moist gray soil	10–20	15
Dry soil, desert	20–35	30
Wet sand	20–30	25
Dry light sand	30–40	35
Asphalt pavement	5–10	7
Concrete pavement	15–35	20
Vegetation		
Short green vegetation	10–20	17
Dry vegetation	20–30	25
Coniferous forest	10–15	12
Deciduous forest	15–25	17
Snow and ice		
Forest with surface snowcover	20–35	25
Sea ice, no snowcover	25–40	30
Old, melting snow	35–65	50
Dry, cold snow	60–75	70
Fresh, dry snow	70–90	80

- Snow and ice brightest
- Deserts, dry soil, and dry grass are very bright
- Forests are dark
- Coniferous (cone-bearing) needleleaf trees are darkest

Energy Balance of Earth’s Surface



shortwave solar radiation

longwave (infrared) radiation

H

rising warm air

LE

evaporated water

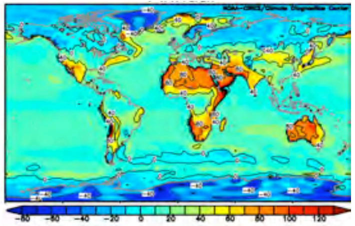
Radiation

Turbulence

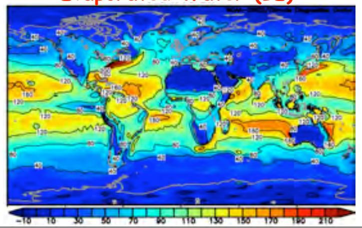
R_s

Energy from the Surface to the Air

Rising Warm Air (H)

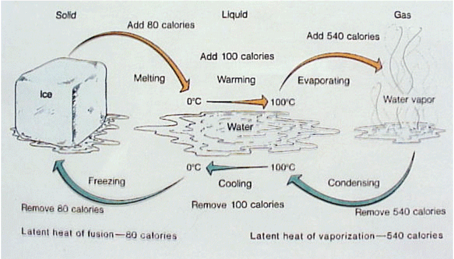


Evaporated Water (LE)



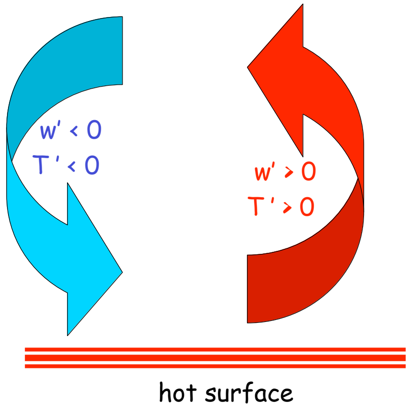
- Energy absorbed at the surface warms the air
- Some of this energy is transferred in rising warm “thermals”
- But more of it is “hidden” in water vapor

It Takes a Lot of Energy to Evaporate Water!



Turbulent Heat Fluxes

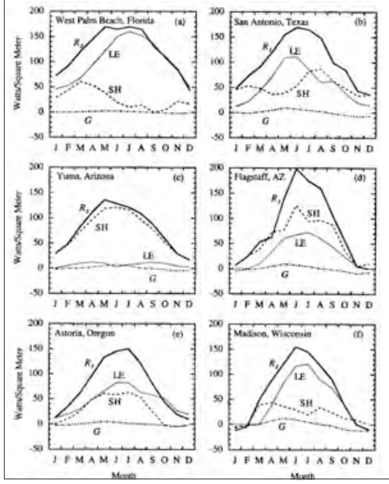
$$w \equiv \overline{w} + w' \qquad T \equiv \overline{T} + T'$$



- Imagine a turbulent eddy over a hot surface
- Updrafts are systematically warmer than downdrafts
- Updraft:
  $\overline{w'T'} > 0$
- Downdraft:
  $\overline{w'T'} > 0$

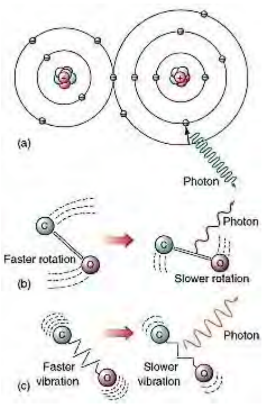
Energy Budget Components

Seasonal Cycles



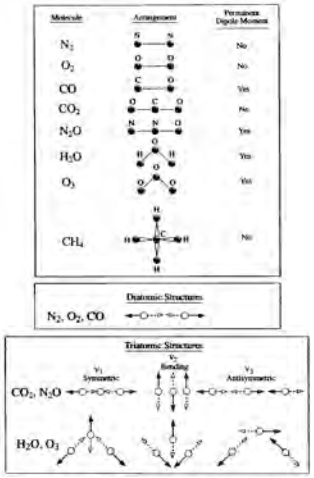
- Seasonal course of due to Sun-Earth geometry
- Moist climates feature near balance of
- Dry climates feature near balance of $R_s \sim H$
- Others are intermediate
  - Spring vs fall in Texas
  - Summer (leaves) vs spring and fall in Wisc
- (H, LE) » G everywhere

Atoms, Molecules, and Photons



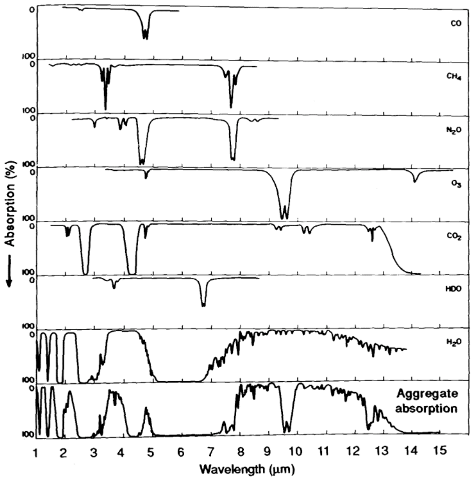
- Atmospheric gases are made of molecules
- Molecules are groups of atoms that share electrons (bonds)
- Photons can interact with molecules
- Transitions between one state and another involve specific amounts of energy

Molecular Absorbers/Emitters



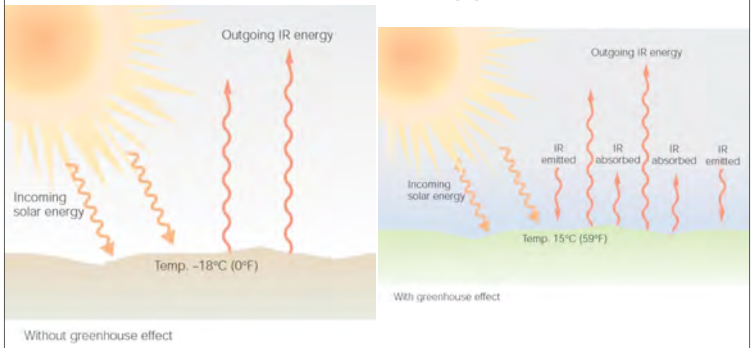
- Different kinds of molecular transitions can absorb/emit very different wavelengths of radiation
- Some molecules are able to interact much more with photons than others
- Different molecular structures produce wavelength-dependent absorptivity/emissivity
- Water vapor (H_2O) and CO_2 are pretty good at this, and abundant enough to make a big difference!

Atmospheric Absorption



- Triatomic modelcules have the most absorption bands
- Complete absorption from 5-8 μ (H_2O) and > 14 μ (CO_2)
- Little absorption between about 8 μ and 11 μ ("window")

Greenhouse Effect



Without greenhouse gases absorbing and emitting longwave radiation the surface temperature would be about 0°F!
Energy from the Sun gets "recycled" between the surface and the atmosphere. Avg surface temp ~ 59°F

Absorption of Solar Radiation

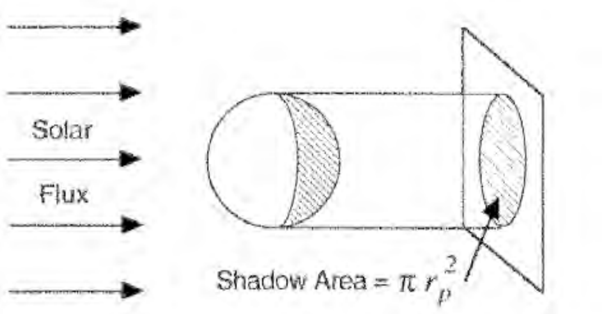


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

Planetary Energy Balance

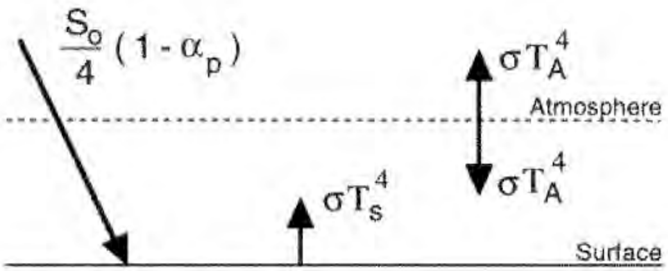
Energy In = Energy Out

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

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

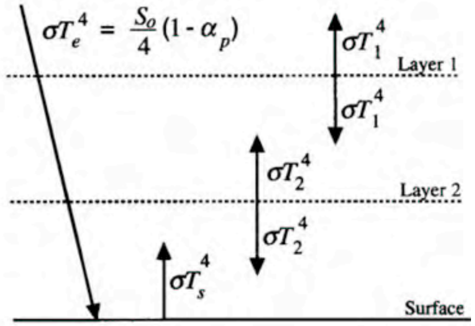
But the observed T_s is about 15° C

Planetary Energy Balance



Atmosphere of hypothetical planet is transparent in SW, but behaves as a blackbody in LW

2-Layer Atmosphere



Two layers of blackbody atmosphere stacked above the surface …

Radiative Balances by Layer

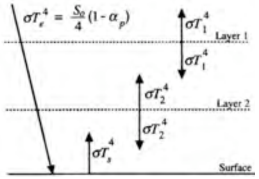
For every layer:
Energy In = Energy Out

planet $$\frac{S_0}{4}(1-\alpha_p) = \sigma T_1^4$$

Upper layer $$\sigma T_2^4 = 2\sigma T_1^4$$

Lower layer $$\sigma T_s^4 + \sigma T_1^4 = 2\sigma T_2^4$$

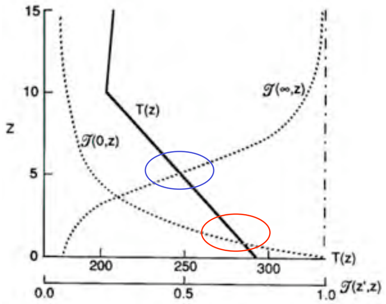
Surface $$\frac{S_0}{4}(1-\alpha_p) + \sigma T_2^4 = \sigma T_s^4$$



$T_2 > T_1$ …

So surface is warmer than with just 1 layer!

Real Atmosphere has Many Layers!

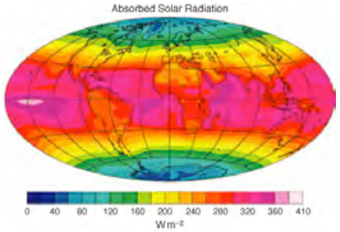


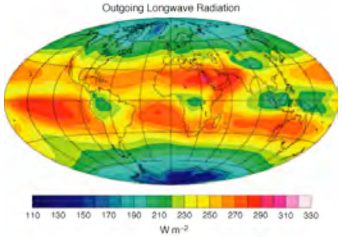
Vertical profiles of atmospheric LW transmission functions and temperature

- Think of upwelling and downwelling infrared as weighted averages of σT^4
- The change in transmission function with height is the **weighting function**
- Downwelling energy at surface comes from lower atmosphere
- Upwelling IR at TOA comes from higher up
- This is the basis for the "greenhouse effect"

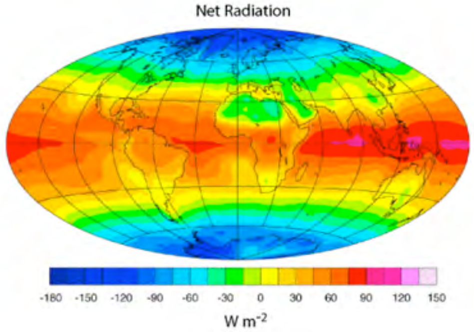
Energy In, Energy Out

- Incoming and outgoing energy must balance on average
- But there are huge differences from place to place
- Way more solar heating in tropics
- Some places (deserts) emit much more than others (high cold clouds over rainforests)





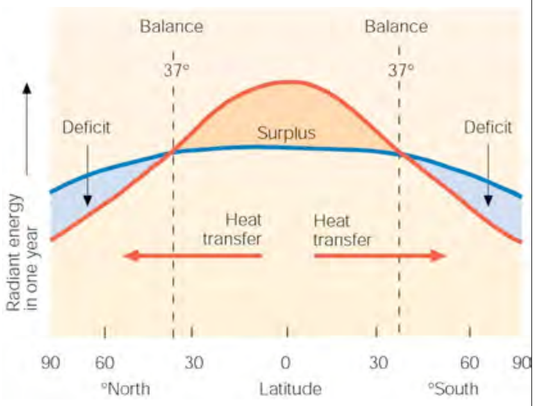
Top of Atmosphere Annual Mean



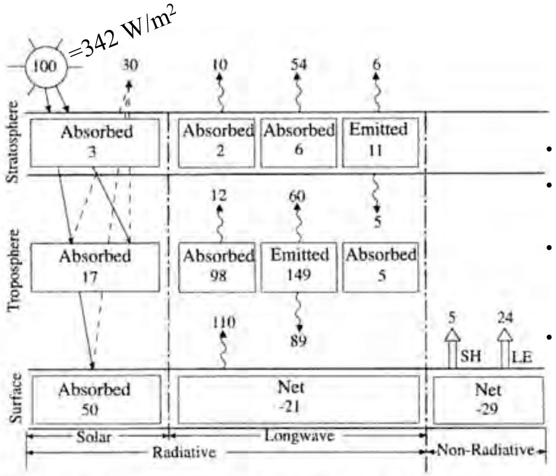
- Incoming solar minus outgoing longwave
- Must be balanced by horizontal transport of energy by atmosphere and oceans!

Earth's Energy Balance

A global balance is maintained by transferring excess heat from the equatorial region toward the poles

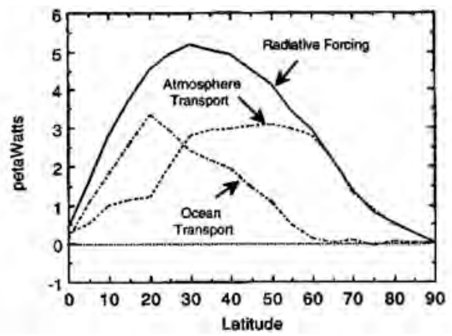


Planetary Energy Budget



- 4 Balances
- Recycling = greenhouse
- Convective fluxes at surface
- LE > H

Energy Transports in the Ocean and Atmosphere



- Northward energy transports in petawatts (10^{15} W)
- "Radiative forcing" is cumulative integral of R_{TOA} starting at zero at the pole
- Slope of forcing curve is excess or deficit of R_{TOA}
- Ocean transport dominates in subtropics
- Atmospheric transport dominates in middle and high latitudes

- *How are these numbers determined?*
- *How well are they known?*

Things to Remember

- All energy exchange with Earth is radiation
- Incoming solar energy is transformed at the surface into sensible heat (warm air) and latent heat (evaporated water)
- Outgoing radiation has longer waves (cooler)
- Longwave radiation is absorbed and re-emitted by molecules in the air (H_2O & CO_2)
- Recycling of energy between air and surface is the "greenhouse effect"
- Regional energy surpluses and deficits drive the atmosphere and ocean circulations