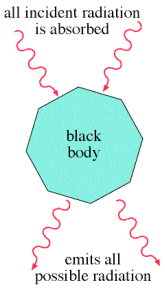
EXPLAIN

2. Earth's Energy Balance

Blackbody Power

$$F_{BB} = \sigma T^4$$

Stefan-Boltzmann Law

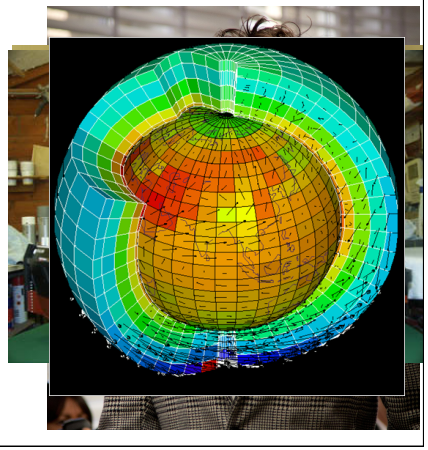


- Total rate of energy emission by a blackbody is proportional to its T x T x T x T = T^4
- Proportionality constant s is measured to be the same for all blackbodies

$s = 5.67 \times 10^{-8}$ is the *Stefan-Boltzmann constant*

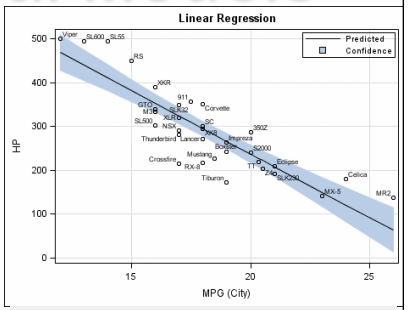
What is a Model?

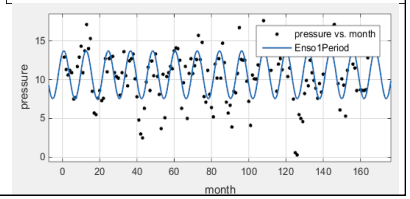
- Models represent reality in a simplified or idealized way
- Used to understand or predict
- Doesn't have to be realistic to be useful



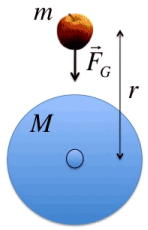
Empirical Models

- Generalized mathematical formulation with adjustable coefficients
- Combinations of
  - polynomials
  - exponential growth & decay
  - Periodic sines and cosines
- Coefficients fit to data (e.g., least squares)
- Interpolation or extrapolation





Deterministic Models

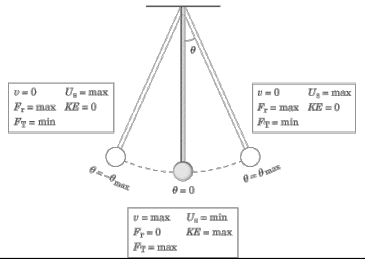


$$F = ma$$

$$\frac{GMm}{r^2} = ma$$

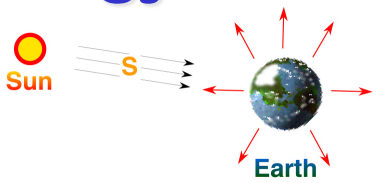
Then, cancelling m on both sides:

$$a = \frac{GM}{r^2} = g$$



- Formulated as "cause and effect"
- Common in physics and chemistry
- Usually take the form of differential equations
- Initial & boundary-value problems
- May still have adjustable coefficients

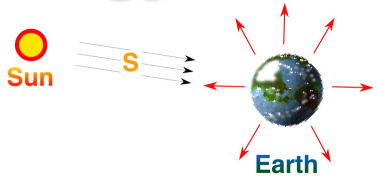
Energy Balance



Energy In = Energy Out

- Let the rate of energy flow from the Sun to the Earth be called F_{in}
- Let the rate of energy flow from the Earth to outer space be called F_{out}

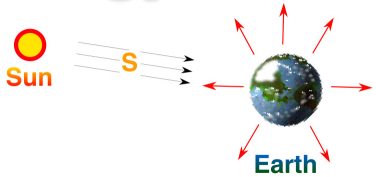
Energy Balance



$F_{in} = F_{out}$

- Assume both Sun and Earth are blackbodies, so $F = s\ T^4$
- F_{in} = absorbed sunlight x daylight area
- $F_{out} = s\ T_{earth}^4$ x total area

Energy Balance

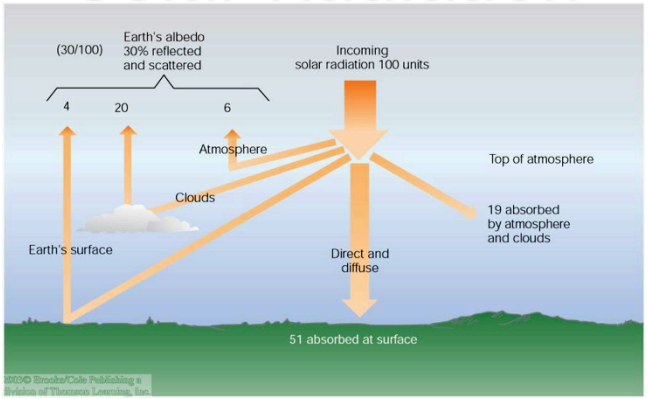


$F_{in} = F_{out}$

F_{in} = Solar brightness x (1 – albedo)
x (area of Earth's shadow)

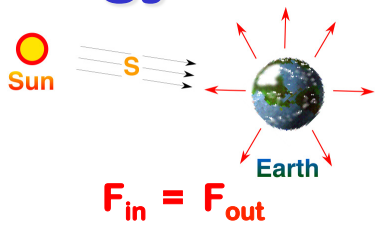
$F_{out} = s\ (T_{earth})^4$ x (area of Earth's surface)

Solar Radiation



- 30% reflected by clouds, air, dust, and surface
- 19% absorbed by the atmosphere (mostly clouds)
- 51% absorbed at the surface

Energy Balance

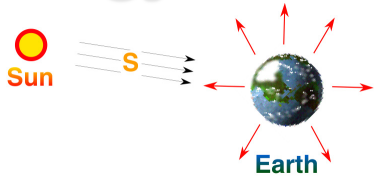


$F_{in} = F_{out}$

F_{in} = Solar brightness x (1 – a) x p r^2

F_{out} = s $(T_e)^4$ x 4p r^2

Energy Balance



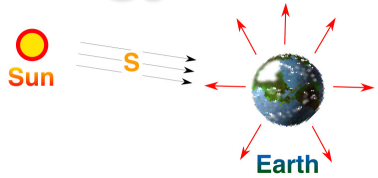
$F_{in} = F_{out}$

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

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

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

Energy Balance

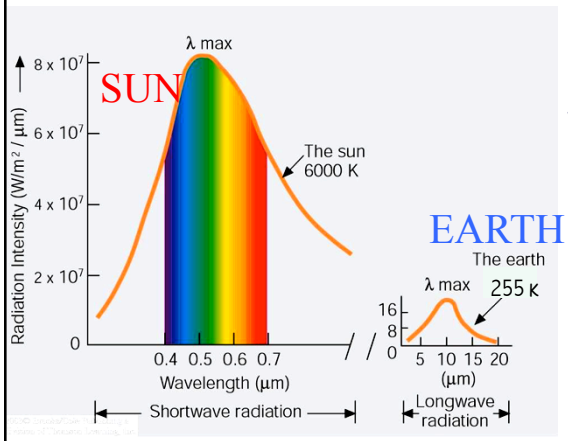


$F_{in} = F_{out}$

$$T = \left(\frac{S(1-\alpha)}{4\sigma}\right)^{1/4} = \left(\frac{(1360 Wm^{-2})(1-0.3)}{4(5.67x10^{-8} Wm^{-2}K^{-4})}\right)^{1/4} = 255K$$

But the observed surface temperature is about 288 K

Earth & Sun Emission

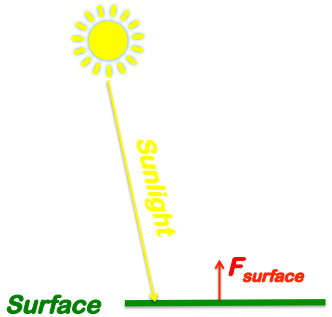


Both are almost perfect blackbodies!

The hot sun radiates at shorter (visible) wavelengths that carry more energy

Energy absorbed by the cooler earth is then re-radiated at longer (thermal infrared) wavelengths

Bare Rock Model

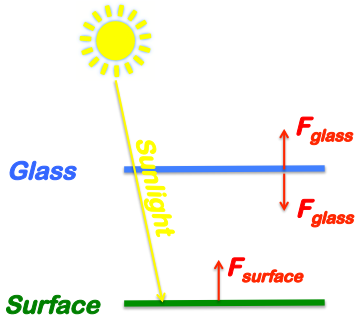


$F_{in} = F_{out}$

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

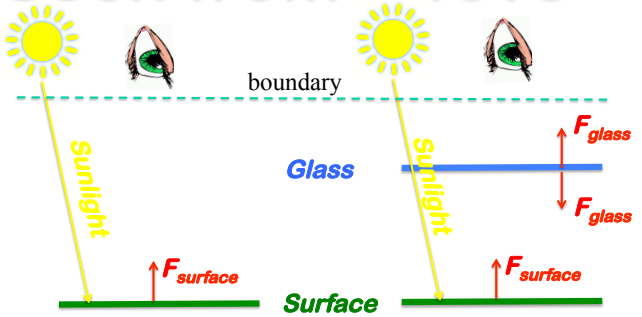
- If sunlight were the only source of energy, the surface of the Earth would be way too cold for life!
- 255 °K = -18 °C = -1 °F

Two-Layer Model



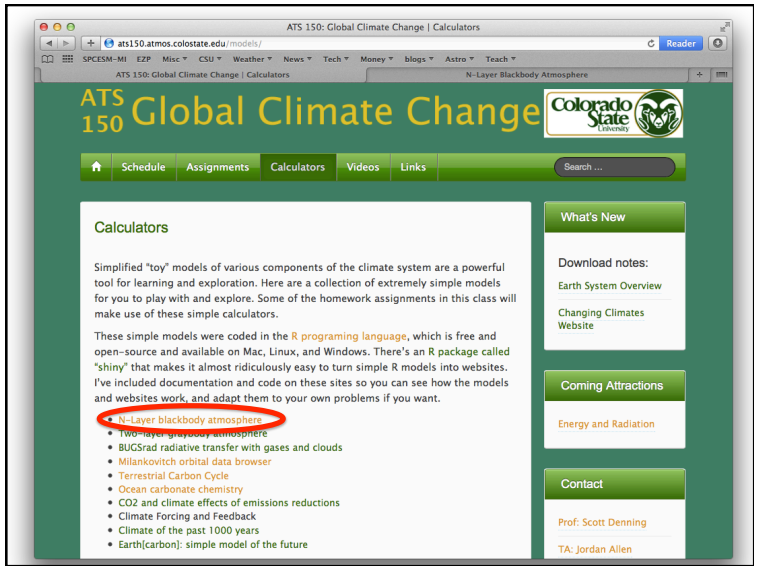
- Now imagine a layer of glass above the solid rock
- Glass is transparent to sunlight
- Glass is opaque to "Earthlight" (thermal IR)

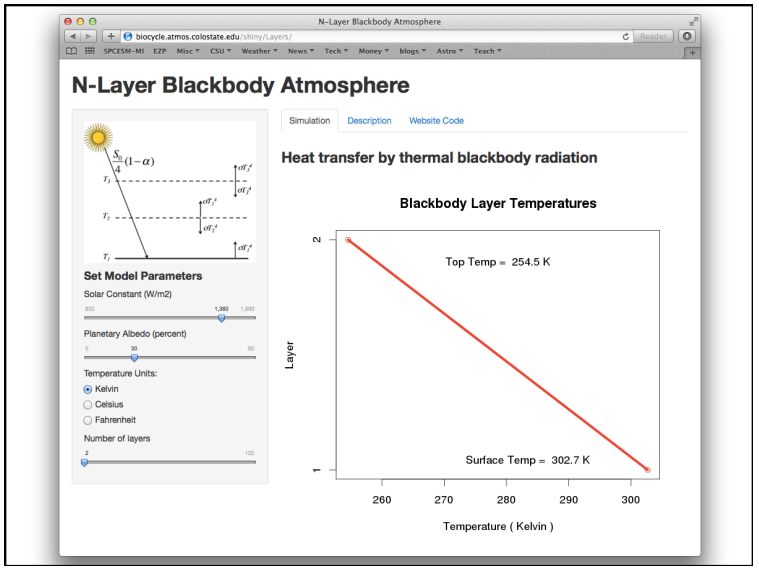
Seen from Above



Both models:

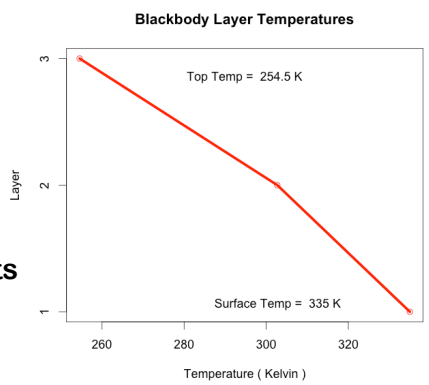
- Absorb the same sunshine
- Reflect the same amount of sunlight back out
- Emit the same amount of Earthlight





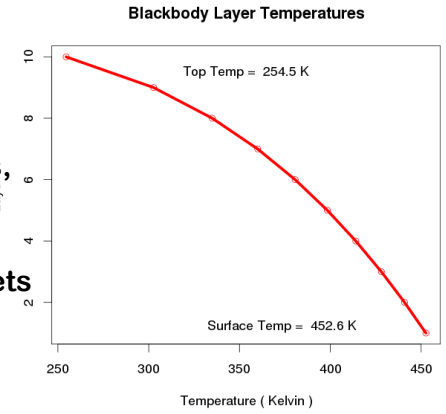
Three Layers

- Top boundary ("skin") temperature is always the same
- As we add layers, the surface gets hotter
- (bathtub drain gets slower)



Ten Layers

- Top boundary ("skin") temperature is always the same
- As we add layers, the surface gets hotter
- (bathtub drain gets slower)



100 Layers!

- Top boundary ("skin") temperature is always the same
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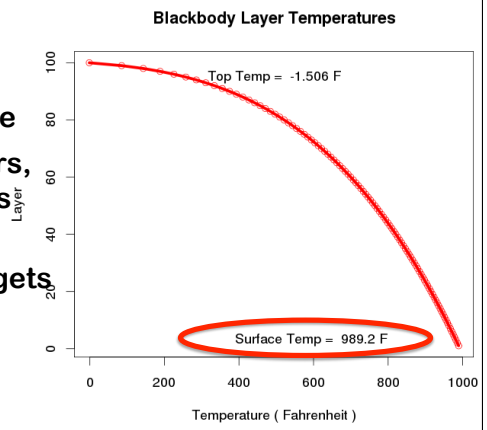
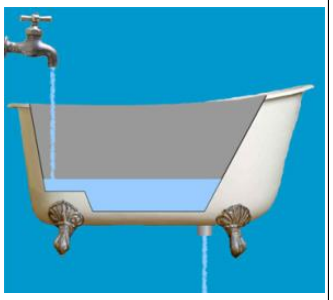


Summary

- Layer models are not meant to be accurate or predictive, just to help us understand how the world works
- Energy balance of "bare rock" model is way too cold to support life!
- Adding a layer of glass makes the surface nice and toasty
- Where did the heat come from?

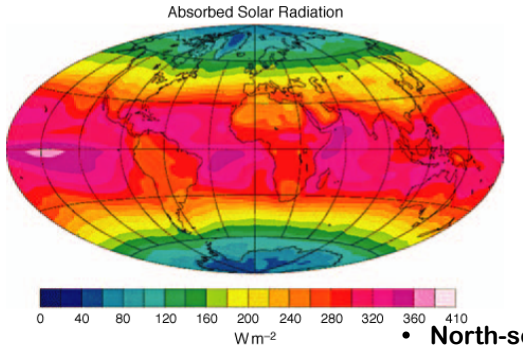
Bathtub Analogy

- If faucet runs faster than drain, level rises
- And vice versa
- Drain runs faster when water is deep
- Adding glass to layer model acts like a clog in the drain
- Water rises until drainage = inflow again



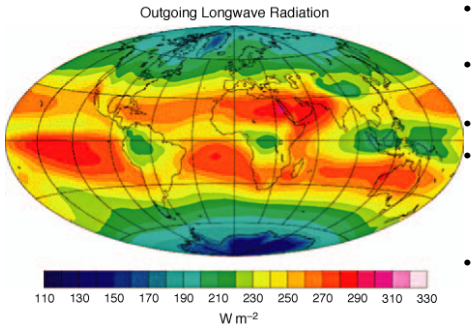
Faucet ~ Sun
Drain ~ Thermal emission
Water level ~ temperature

Energy In



- North-south contrast
- Land-sea contrast
- Ice and snow
- Deserts vs forests

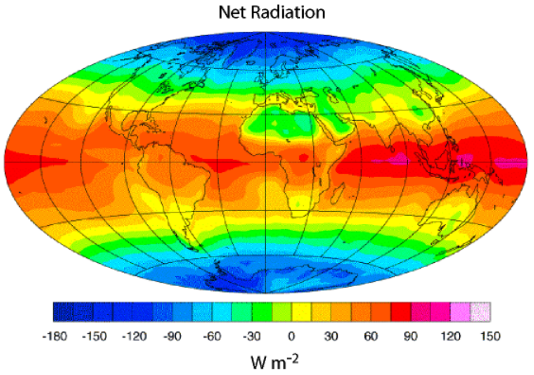
Energy Out



Annual Mean

- Given by $\varepsilon\sigma T^4$ (which T?)
- Combined surface and atmosphere effects
- Decreases with latitude
- Maxima over subtropical highs (clear air neither absorbs or emits much)
- Minima over tropical continents (cold high clouds)
- Very strong maxima over deserts (hot surface, clear atmosphere)

Energy In minus Energy Out

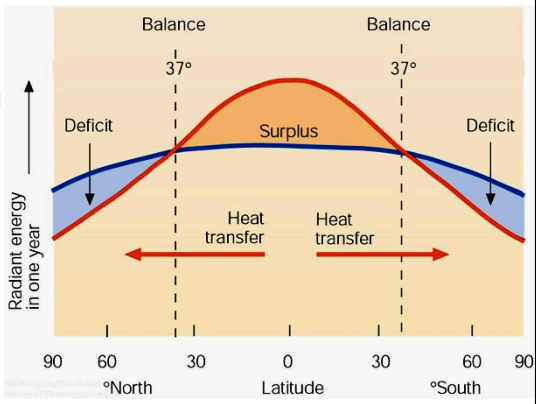


- Incoming solar minus outgoing longwave
- Must be balanced by horizontal transport of energy by atmosphere and oceans!

Earth's Energy Balance

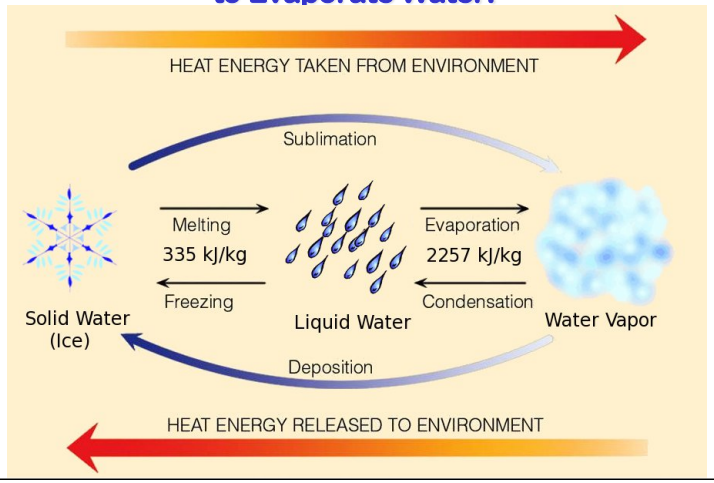
Earth's annual energy balance between solar insolation and terrestrial infrared radiation is global but not local

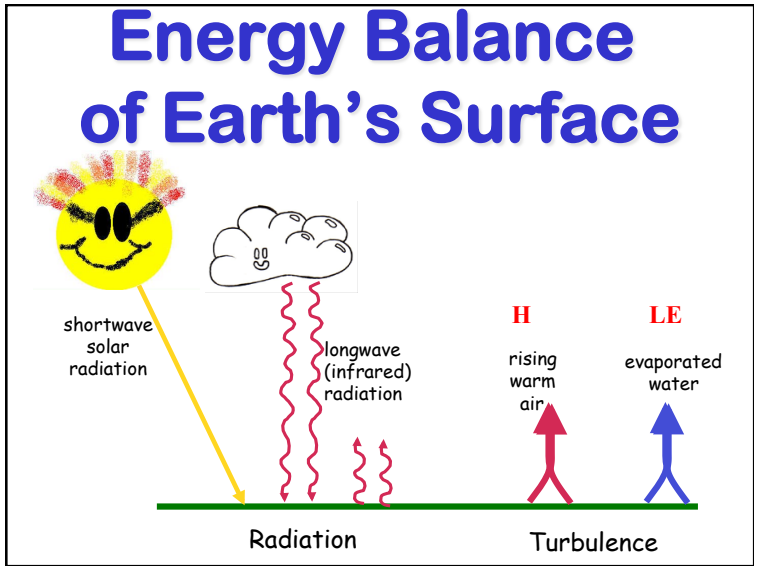
The global balance is maintained by transferring excess heat from the equatorial region toward the poles

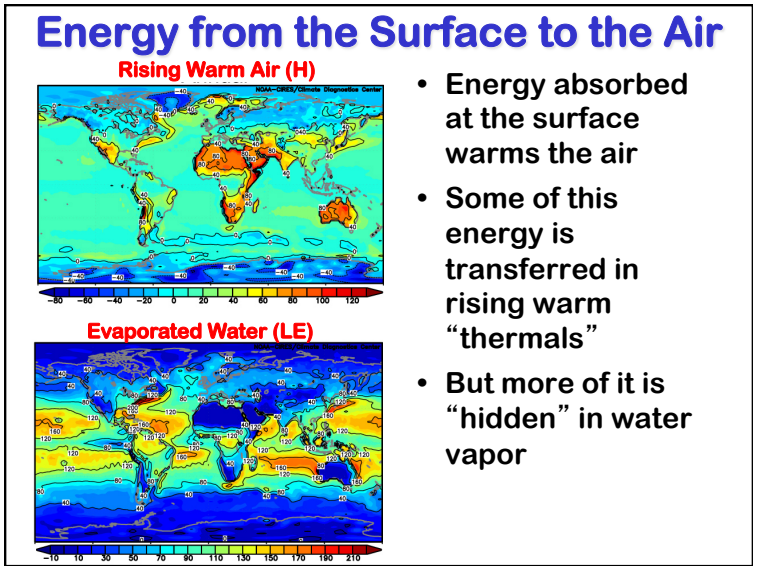


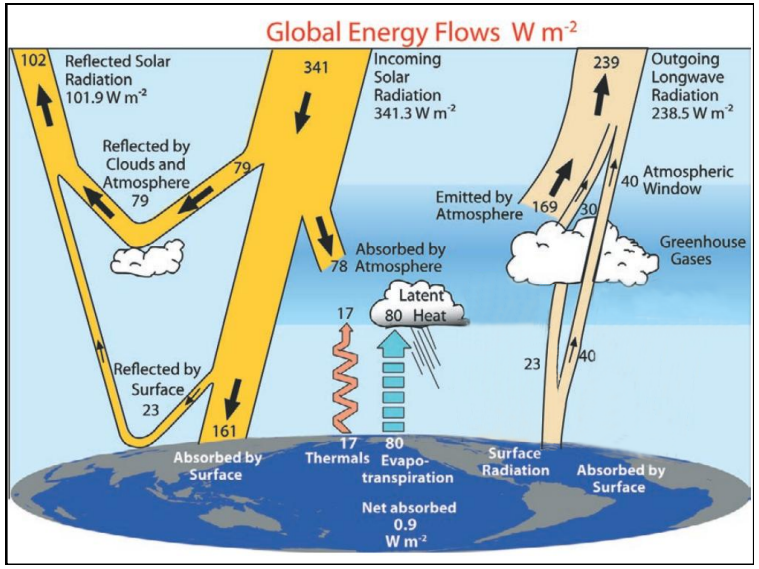
It Takes a Lot of Energy

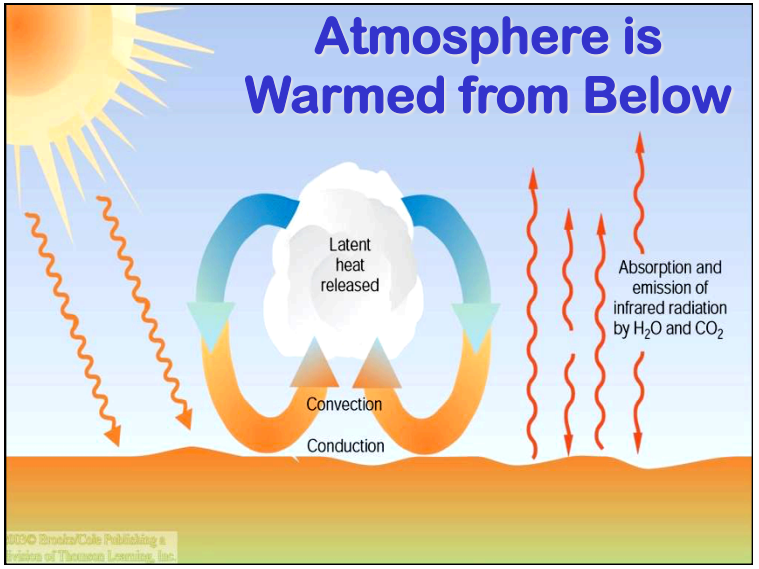
to Evaporate Water!




Energy Balance of Earth's Surface
shortwave solar radiation
longwave (infrared) radiation
H
rising warm air
LE
evaporated water
Radiation
Turbulence


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


Global Energy Flows W m-2
102 Reflected Solar Radiation 101.9 W m-2
341 Incoming Solar Radiation 341.3 W m-2
239 Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere 79
79
Emitted by Atmosphere 169
40 Atmospheric Window
30
Absorbed by Atmosphere 78
Greenhouse Gases
Latent 80 Heat
17
Reflected by Surface 23
23
40
161
Absorbed by Surface
17 Thermals
80 Evapo-transpiration
Surface Radiation
Absorbed by Surface
Net absorbed 0.9 W m-2

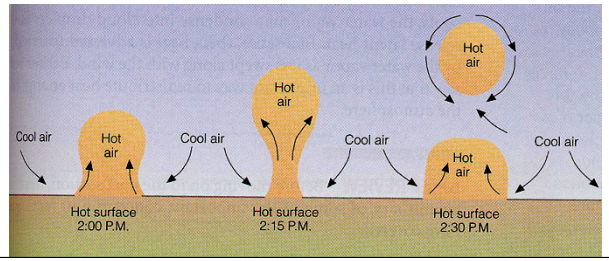

Atmosphere is Warmed from Below
Latent heat released
Absorption and emission of infrared radiation by H2O and CO2
Convection
Conduction

Vertical Structure is Crucial

- The world is a big place, but the atmosphere is very thin, and most of it is close to the ground
  - About 15% of the atmosphere is below our feet
  - At the top of Long's Peak, the figure is 40%
  - You are closer to outer space than you are to Denver!
- Changes in atmospheric temperature with height are responsible for the "Greenhouse Effect," which keeps us from freezing to death

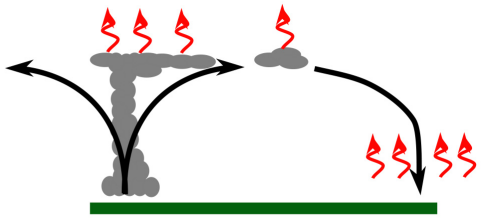
Heating by Convection

- Sunlight warms the ground
- Ground warms adjacent air by conduction
- Hot air forms rising air "bubbles" (thermals) leading to convection … heats the air, but cools the surface!



The Job of the Atmosphere

is to let the energy out!



"Piles up" in tropics

"Escapes" near poles and aloft

The movement of the air (and oceans) allows energy to be transported to its "escape zones!"

Remember

- Heat in minus heat out = change of heat
- Earth gets all its energy from the Sun
- Earth emits all its energy in thermal infrared
- Atmosphere is selectively transparent:
  - Lets solar radiation in
  - Absorbs & re-emits thermal radiation
- Almost all emission to space is from very high up where its very cold
- Job of the atmosphere & oceans is to lift heat up and move it to poles where it can be emitted to space