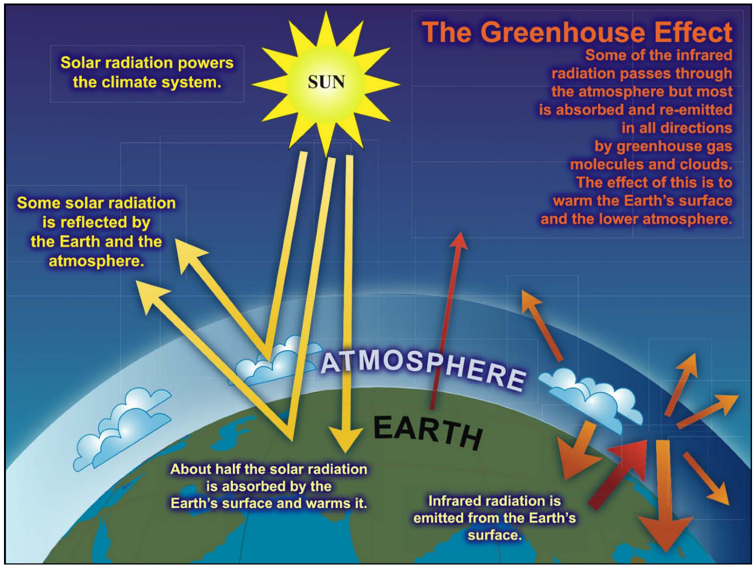


The Greenhouse Effect

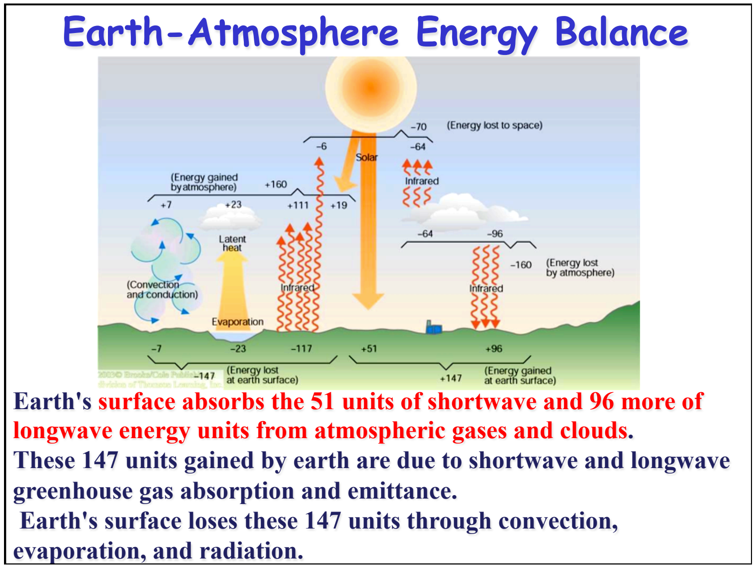
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.

Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

About half the solar radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

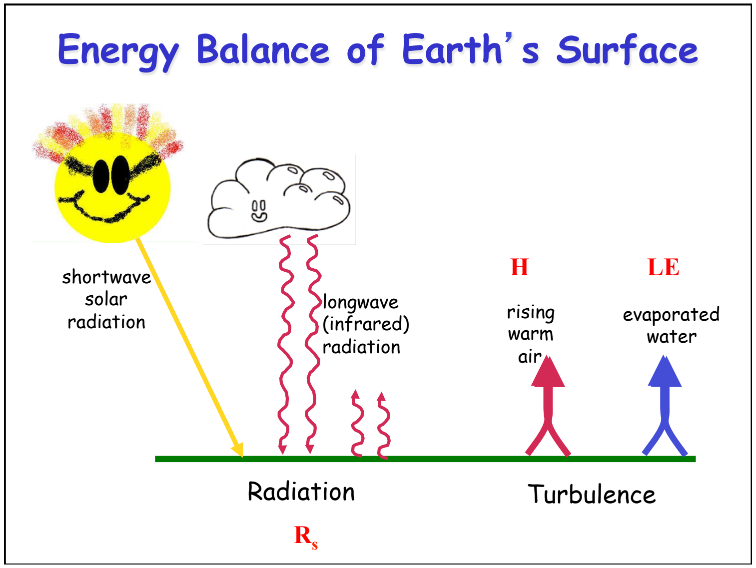


Earth-Atmosphere Energy Balance

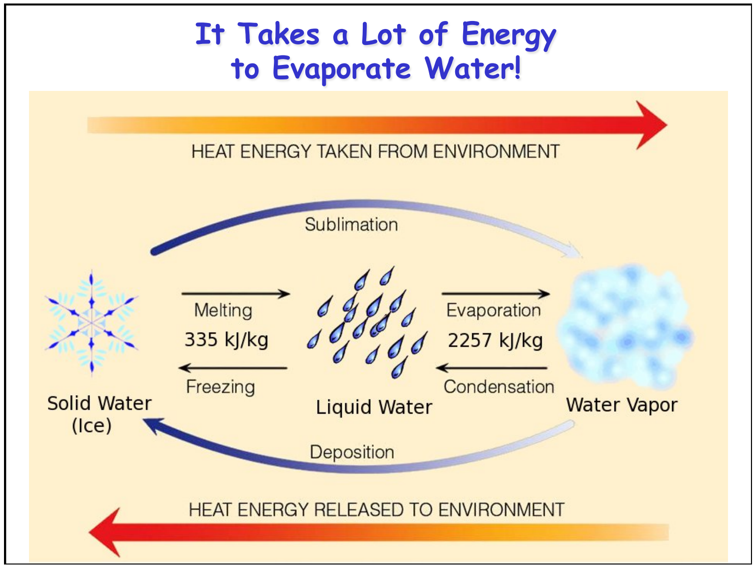
Earth's surface absorbs the 51 units of shortwave and 96 more of longwave energy units from atmospheric gases and clouds.

These 147 units gained by earth are due to shortwave and longwave greenhouse gas absorption and emittance.

Earth's surface loses these 147 units through convection, evaporation, and radiation.



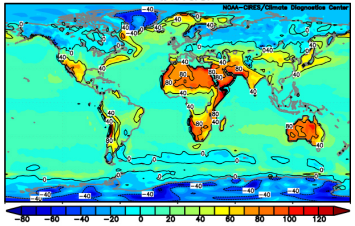
Energy Balance of Earth's Surface



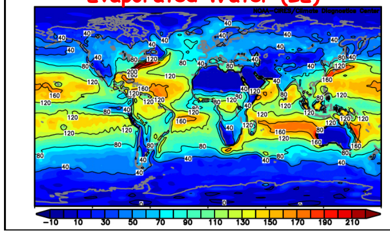
It Takes a Lot of Energy to Evaporate Water!

Energy from the Surface to the Air

Rising Warm Air (H)

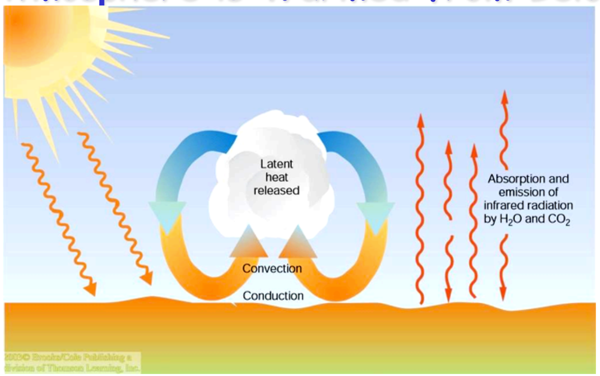


Evaporated Water (LE)



- 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

Atmosphere is Warmed from Below

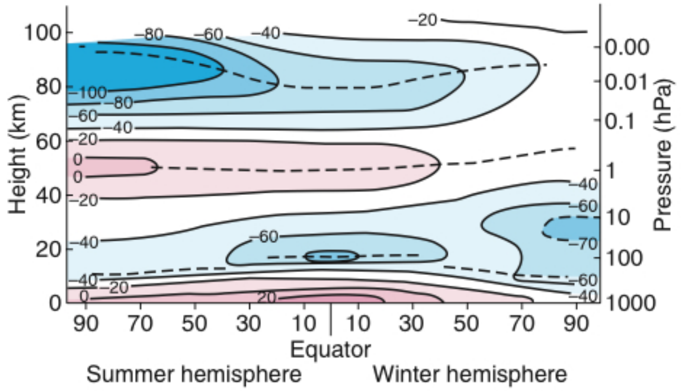


Solar radiation passes first through the upper atmosphere, but only after absorption by earth's surface does it generate sensible heat to warm the ground and generate longwave energy.
This heat and energy at the surface then warms the atmosphere from below.

Vertical Structure is Crucial

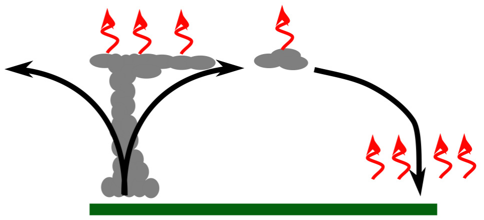
- The world is a big place, but the atmosphere is very thin, and most of it is close to the ground
  - About 15% of the atmosphere is below our feet
  - At the top of Long's Peak, the figure is 40%
  - You are closer to outer space than you are to Denver!
- Changes in atmospheric temperature with height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

Vertical Structure of the Air



The Job of the Atmosphere

is to let the energy out!



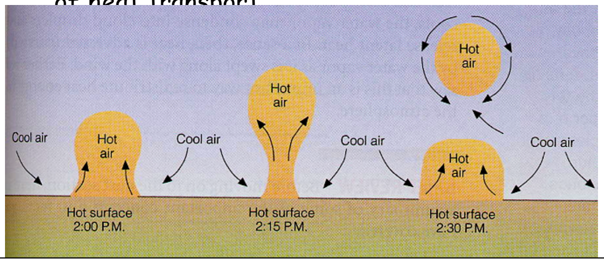
Hot **Cold**

"Piles up" in tropics "Escapes" near poles and aloft

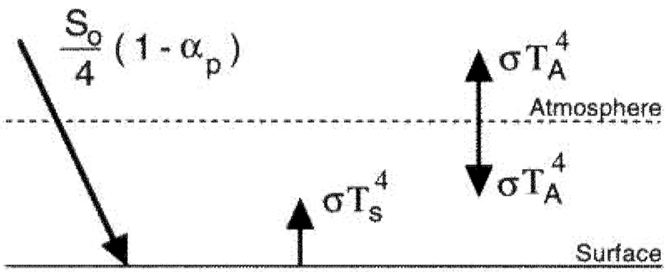
The movement of the air (and oceans) allows energy to be transported to its "escape zones!"

Atmospheric Heating by Convection

- Sunlight warms the ground
- Ground warms adjacent air by conduction
  - Poor thermal conductivity of air restricts heating to a few cm
- Hot air forms rising air "bubbles" (thermals) leading to convection … heats the air, but cools the surface!
  - Mechanical mixing due to wind enhances this mode of heat transport

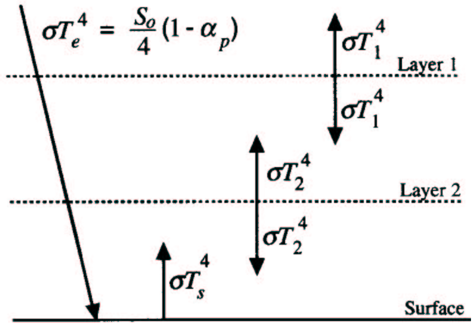


Planetary Energy Balance



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

2-Layer Atmosphere



Transmission-weighted fluxes can be used to develop a simple 2-layer atmospheric RT balance

Radiative Balances by Layer

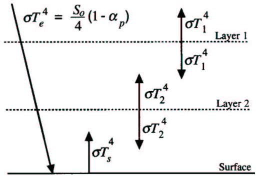
For every layer:
Energy In = Energy Out

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

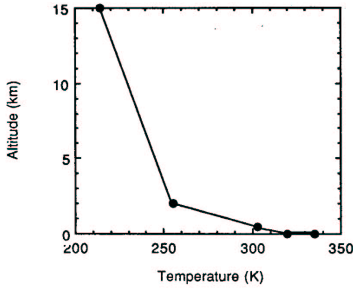
L1 $$\sigma T_2^4 = 2\sigma T_1^4$$

L2 $$\sigma T_s^4 + \sigma T_1^4 = 2\sigma T_2^4$$

Surface $$\frac{S_0}{4}(1-\alpha_p) + \sigma T_2^4 = 2\sigma T_s^4$$



2-Layer BB Atmosphere (cont'd)



Vertical temperature profile for 2-layer atmosphere, with thin graybody layers at top and bottom.

Very unrealistic lapse rate!! Why?

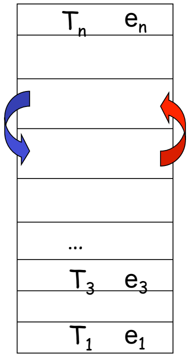
- Solving energy budgets for all layers simultaneously gives

$$T_S^4 = 3\frac{(S_0/4)(1-\alpha_p)}{\sigma} = 3T_e^4$$

- Recall from Ch 2 that a 1 layer B-B atmosphere produces $T_s^4 = 2T_e^4$
- In general, an n-layer B-B atmosphere will have $T_s^4 = (n+1)T_e^4$

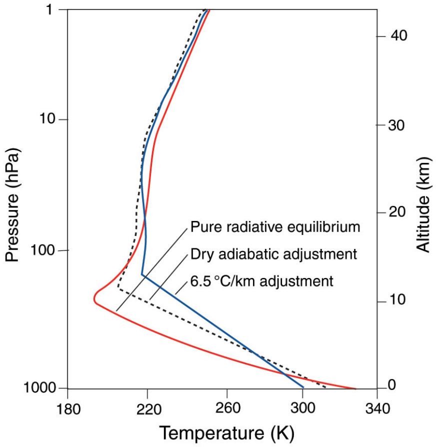
Radiative-Convective Models (a recipe)

- Consider a 1-D atmosphere
- Specify solar radiation at the top, emissivity of each layer
- Calculate radiative equilibrium temperature for each layer
- Check for static stability
- If layers are unstable, mix them!
  - (e.g. if G > G$_d$, set both T's to mass-weighted mean of the layer pair)
- Add clouds and absorbing gases to taste



Manabe and Strickler (1964)

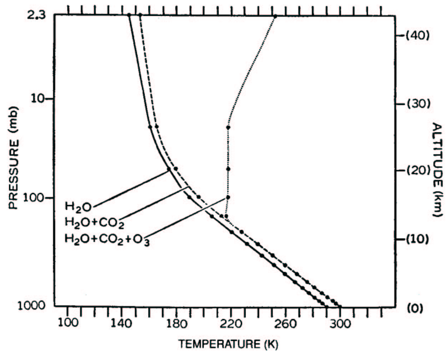
Radiative-Convective Equilibrium



- Pure radiative equilibrium is way too hot at surface
- Adjusting to G$_d$ still too steep
- Adjusting to observed 6.5 K km^{-1} produces fairly reasonable profile:
  - Sfc temp (still hot)
  - Tropopause (OK)
  - Stratosphere (OK)

Radiative-Convective Equilibrium

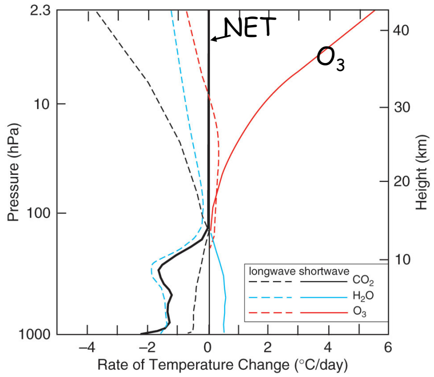
Effect of Different Absorbers



- Water vapor alone … atmosphere is cooler
- $H_2O + CO_2$ … almost 10 K warmer
- $H_2O + CO_2 + O_3$ … stratosphere appears!

Radiative-Convective Equilibrium

Radiative Heating Rates

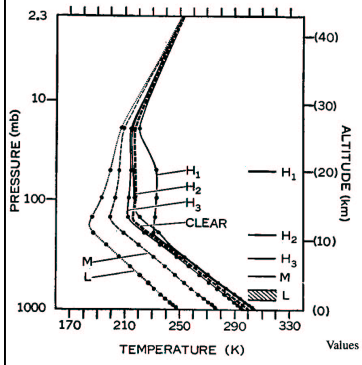


[Adapted from S. Manabe and R. F. Strickler, *J. Atmos. Sci.*, **21**, p. 373 (1964).]

- NET combines all SW and LW forcing
- Heating and cooling nearly balance in stratosphere
- Troposphere cools strongly (~ 1.5 K/day)
- How is net tropospheric cooling balanced?

Radiative-Convective Equilibrium

Effects of Clouds



- Clouds absorb LW
- Clouds reflect SW
- Which effect “wins?”
- Depends on emitting T
- For low clouds, $sT^4 \sim sT_s^4$, so SW effect is greater
- For high clouds, $sT^4 \ll sT_s^4$ so LW effect “wins”
- High clouds warm
- Low clouds cool

Details are sensitive to optical properties and distributions of clouds, but *remember the basic conclusion*

Values of Cloud Shortwave Reflectivity and Absorptivity and Fractional Area Coverage Assumed in Manabe and Strickler (1964)

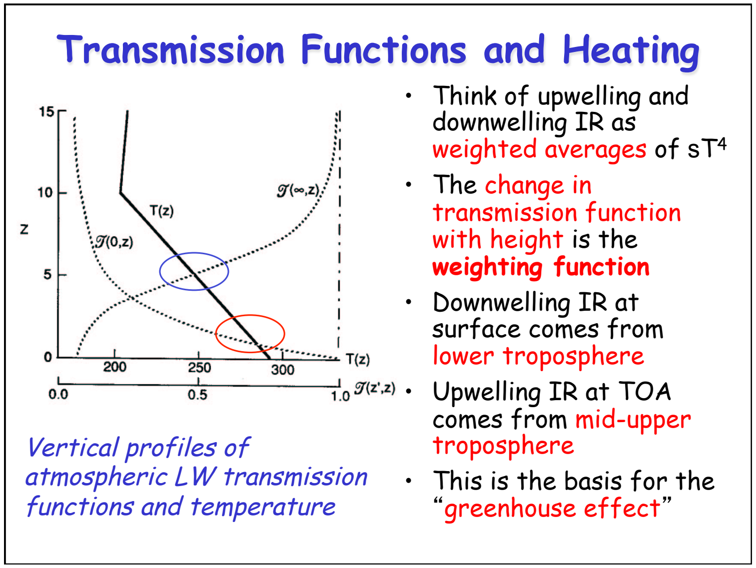
Type	SW reflectivity	SW absorptivity	% of area
High (cirrus)	0.21	0.005	0.228
Medium (cumulus)	0.48	0.020	0.090
Low (stratus)	0.69	0.035	0.313

Global Mean Cloud Radiative Forcing

	Average	Cloud-free	Cloud forcing
OLR	234	266	+31
Absorbed solar radiation	239	288	−48
Net radiation	+5	+22	−17
Albedo	30%	15%	+15%

Radiative flux densities are given in W m^{-2} and albedo in percent. [From Harrison *et al.* (1990), © American Geophysical Union.]

- Clouds increase planetary albedo from 15% to 30%
- This reduces absorbed solar by 48 W m^{-2}
- Reduced solar is offset by 31 W m^{-2} of LW warming (greenhouse)
- So total cloud forcing is -17 W m^{-2}
- Clouds cool the climate. By how much? How might this number change if cloudiness increased?



Transmission Functions and Heating

Vertical profiles of atmospheric LW transmission functions and temperature

- Think of upwelling and downwelling IR as weighted averages of sT^4
- The change in transmission function with height is the **weighting function**
- Downwelling IR at surface comes from lower troposphere
- Upwelling IR at TOA comes from mid-upper troposphere
- This is the basis for the “greenhouse effect”