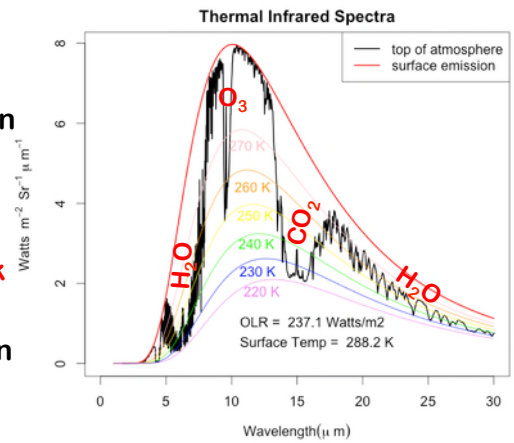
Vertical Variations
what holds the air up?

ATS 150
Spring 2015
Lecture 6

Please read Chapter 5
in Archer Textbook

Greenhouse Effect

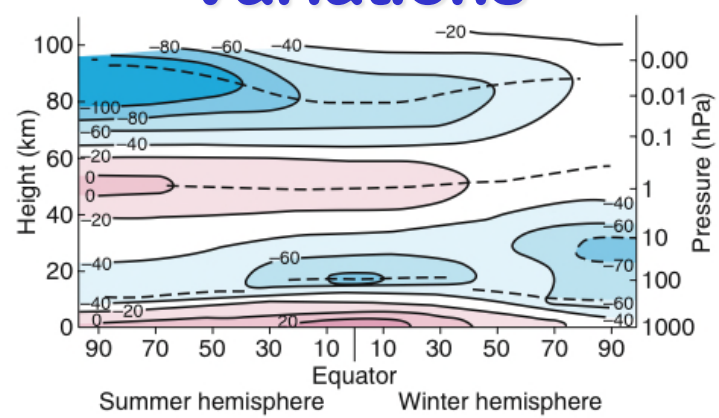
- Hot surface emits directly to space in window region
- Cold upper layers emit to space in optically thick regions
- Total emission much less than from sfc



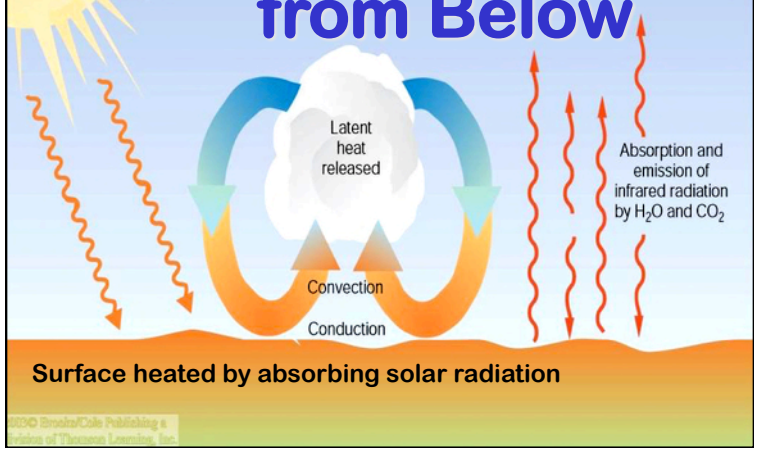
Vertical Variations are Crucial

- 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

Global Temperature Variations



Air is Warmed from Below



Convective Mixing

- Convective mixing of the atmosphere cools the surface, and warms the upper air
- Greenhouse Effect depends on thermal radiation being emitted from the cold upper layers
- So the more convective mixing we get, the less powerful the Greenhouse Effect will be!

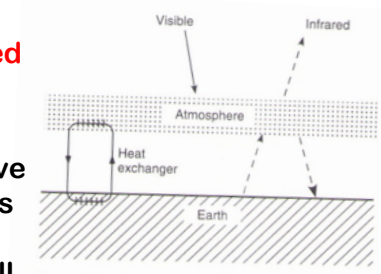


Figure 5-1 The Layer Model from Chapter 3 with an added heat exchanger, capable of partially or completely equalizing the temperatures of the two layers.

"Ideal Gas Law"

$$p = \rho R T$$

pressure ($N\ m^{-2}$)

density ($kg\ m^{-3}$)

"gas constant" ($J\ K^{-1}\ kg^{-1}$)

temperature (K)

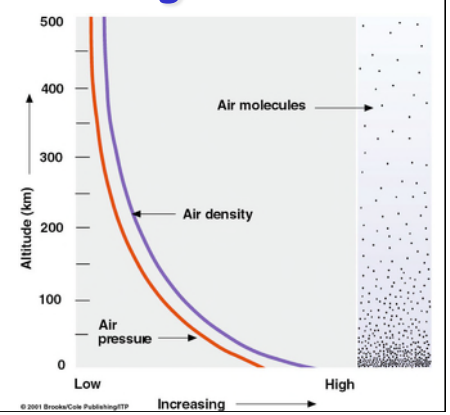
- *Direct* relationship between density and pressure
- *Inverse* relationship between density and temperature
- *Direct* relationship between temperature and pressure

R is another one of those numbers we have to measure, like σ. We call these "physical constants."

$R = 287\ J\ K^{-1}\ kg^{-1}$

Pressure and Density

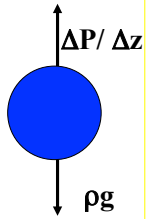
- Gravity holds most of the air close to the ground
- The weight of the overlying air is the pressure at any point



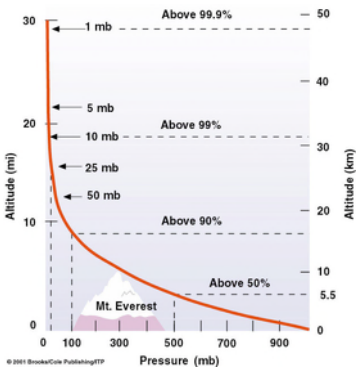
What Holds the Air Up?

A balance between gravity and the pressure gradient force.

$\Delta P / \Delta z = \rho g$



A "pressure gradient force" pushes from high to low pressure.



Buoyancy

- An "air parcel" rises in the atmosphere when its density is less than its surroundings
- Remember the Ideal Gas Law: $p = \rho R T$
- R is a constant. At any given place, pressure is also pretty constant, so density ρ depends mostly on temperature T
- When T goes up, ρ **goes down and vice versa**
- "hot air rises, and cold air sinks"
- So anything that adds heat to the air makes it buoyant, and anything that cools it makes it sink

Height vs Heat

An "air parcel" can have different kinds of energy … consider two kinds:

- Gravitational potential energy
  - Because of its height (we use "z" in meters)
  - Potential energy = g z
  - g is the acceleration due to Earth's gravity. This is yet another of those "physical constants" g = 9.81 m s^{-2}
- Internal heat energy
  - due to the internal kinetic energy of its molecules (temperature)
  - $H = c_p T$, c_p = 1004 J K^{-1} kg^{-1} (heat capacity)

Static Energy

- Total "static energy" means the part the air has just sitting around (not kinetic energy from blowing as wind)
- Static energy is the sum of gravitational potential energy and heat energy

$$S = PE + H$$
$$= gz + c_p T$$

Static energy is measured in Joules per kilogram

Trading Height for Heat

Suppose a parcel exchanges no energy with its surroundings
… e.g. no heating by radiation, evaporation

This means no changes in static energy S

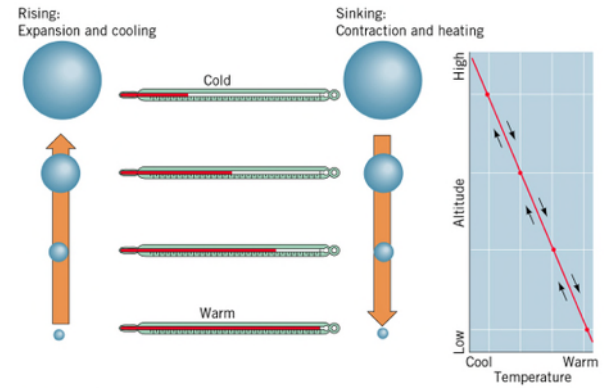
$$\Delta S = 0 = c_p \Delta T + g \Delta z$$

$$c_p \Delta T = -g \Delta z$$

$$\frac{\Delta T}{\Delta z} = -\frac{g}{c_p} = -\frac{(9.81\, ms^{-2})}{(1004\, J\, K^{-1}\, kg^{-1})} = -9.8\, K\, km^{-1}$$

"Dry lapse rate"

Dry Lapse Rate



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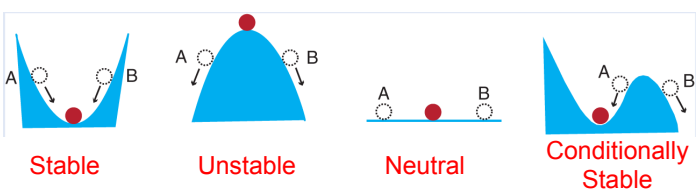
10 degrees C per kilometer

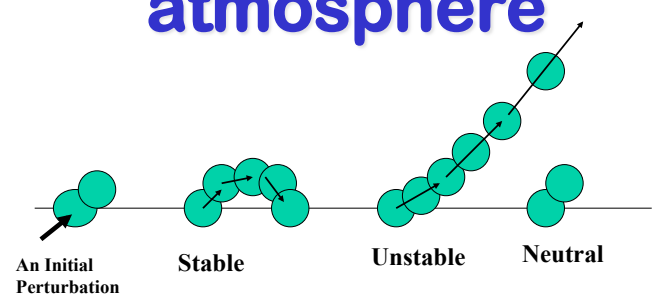
Warming and Cooling due to changing pressure

Stable and Unstable Equilibria



- Stable: when perturbed, system accelerates back toward equilibrium state
- Unstable: when perturbed, system accelerates away from equilibrium state

Stability in the atmosphere



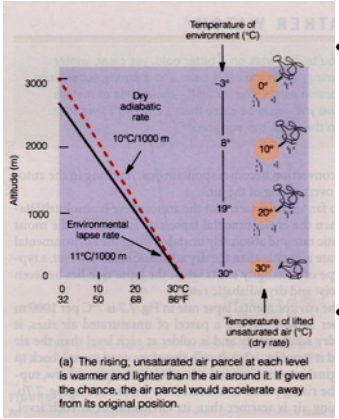
If an air parcel is displaced from its original height it can:
Return to its original height - Stable
Accelerate upward because it is buoyant - Unstable
Stay at the place to which it was displaced - Neutral

Stability and the Dry Lapse Rate

- A rising air parcel cools according to the dry lapse rate (10 °C per km)
- If rising, cooling air is:
  - warmer than surrounding air it is less dense and buoyancy accelerates the parcel upward … UNSTABLE!
  - colder than surrounding air it is more dense and buoyancy opposes (slows) the rising motion … STABLE!

Unstable Atmosphere

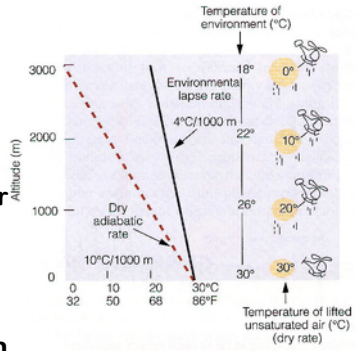
- The atmosphere is unstable if the actual lapse rate exceeds the dry lapse rate (air cools more than 10 C/km)
- This situation is rare in nature (not long-lived)
  - Usually results from surface heating and is confined to a shallow layer near the surface
  - Vertical mixing eliminates it
- Mixing results in a dry lapse rate in the mixed layer, unless condensation (cloud formation) occurs



(a) The rising, unsaturated air parcel at each level is warmer and lighter than the air around it. If given the chance, the air parcel would accelerate away from its original position.

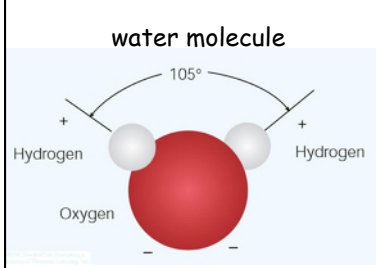
Stable Atmosphere

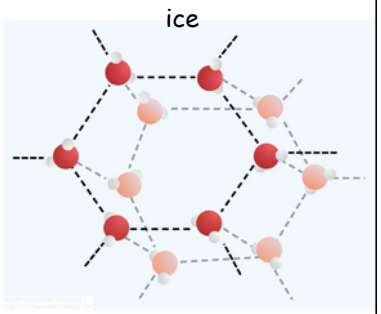
- The atmosphere is stable if the actual lapse rate is less than the dry lapse rate (air cools less than 10°C/km)
- This situation is common in nature (happens most calm nights, esp in winter)
  - Usually results from surface cooling and is confined to a shallow layer near the surface
  - Vertical mixing or surface heating eliminates it
- Holds cold air & pollution down against surface



(a) Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position

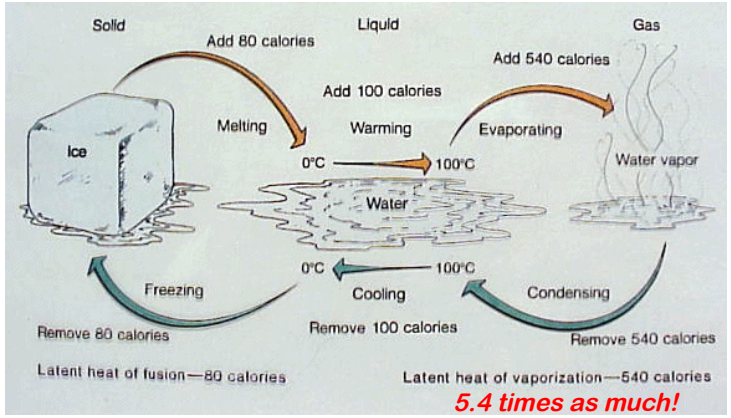
Molecular Structure of Water





Water's unique molecular structure and hydrogen bonds enable all 3 phases to exist on Earth.

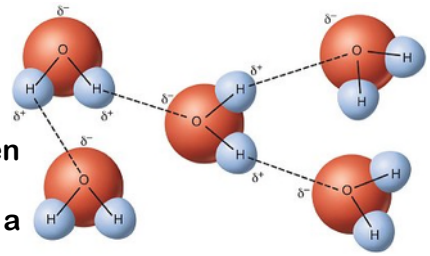
"Latent" (hidden) Energy associated with phase changes



5.4 times as much!

Why does it take so much energy to evaporate water?

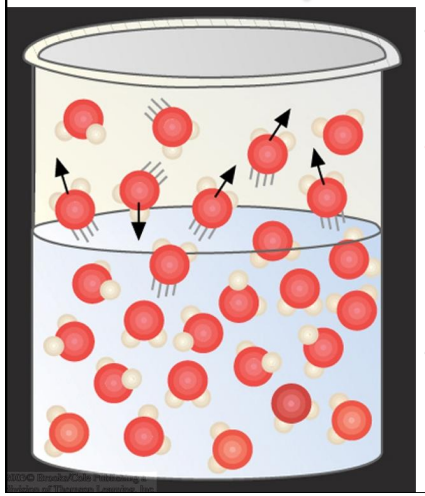
- In the liquid state, adjacent water molecules attract one another
- This same hydrogen bond accounts for surface tension on a free water surface



"plus" charge on hydrogen in one water molecule attracts the "minus" charge on a neighbor's oxygen

column of water "sticks together"

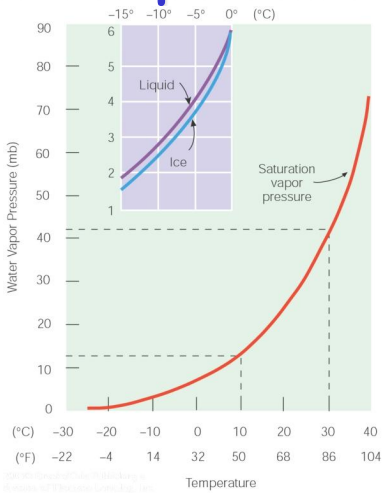
Water vapor saturation



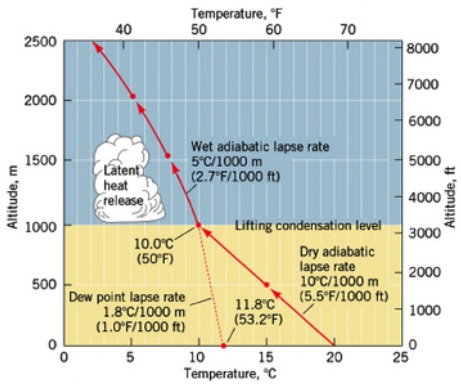
- Water molecules move between the liquid and gas phases
- When the rate of water molecules entering the liquid equals the rate leaving the liquid, we say the air is saturated with water vapor
- Saturated air, relative humidity = 100%

Saturation and Temperature

- The saturation vapor pressure of water increases with temperature
- At higher T, faster water molecules in liquid escape more frequently causing equilibrium water vapor concentration to rise
- We sometimes say "*warmer air can hold more water*"



Moist Lapse Rate

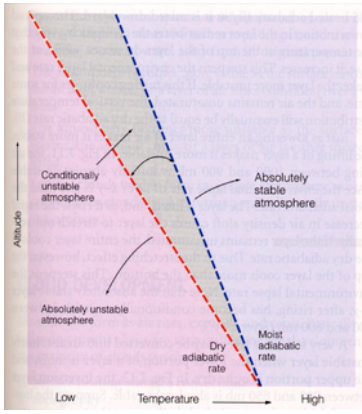


- Parcel cools as it rises (trading height for heat)
- When it cools enough to reach its dewpoint, water condenses
- Latent heat warms the air

Rising air with condensing water cools more slowly with height than dry air

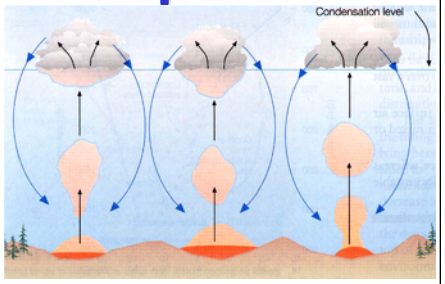
Conditionally unstable air

- If the environmental lapse rate falls between the moist and dry lapse rates:
  - The atmosphere is unstable for saturated air parcels but stable for dry air parcels
  - This situation is termed *conditionally unstable*
- This is the most typical situation in the troposphere



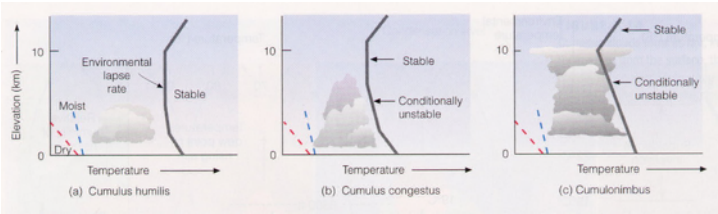
Fair weather cumulus cloud development

- Buoyant thermals due to surface heating
- They cool at dry lapse rate (10°K/km)
- Cloud forms when rising air cools to its dewpoint (RH ~ 100%)
- Sinking dry air between cloud elements

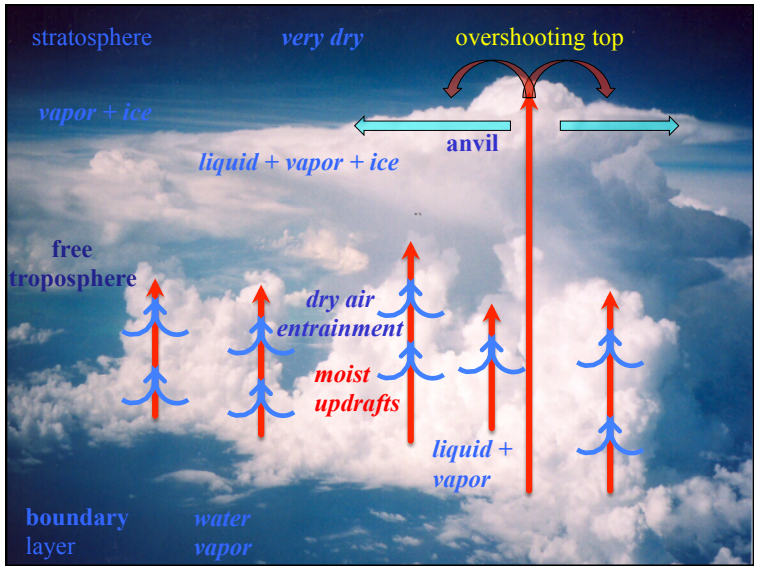


This is how the lower atmosphere mixes heat, moisture, and pollution up and away from the surface

Growth of Taller Clouds



- A less stable atmospheric (steeper lapse rate) profile permits greater vertical motion
- Lots of low-level moisture permits latent heating to warm parcel, accelerating it upward
- Rising moist air may eventually hit the warmer stratosphere where it heavy (acts like a lid)



Thunderstorms, Lapse Rates, and Climate Change

- Greenhouse Effect depends on thermal radiation being emitted from the cold upper layers
- So the more convective mixing we get, the less powerful the Greenhouse Effect will be!

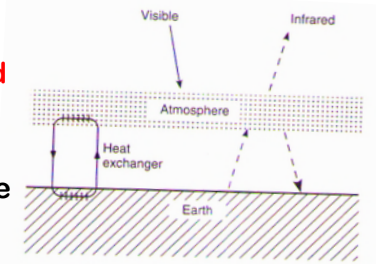


Figure 5-1 The Layer Model from Chapter 3 with an added heat exchanger, capable of partially or completely equalizing the temperatures of the two layers.