Equation of State
(a.k.a. the "Ideal Gas Law")

$$p = \rho R T$$

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

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

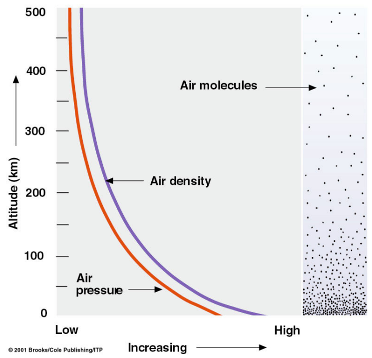
"gas constant" ($J\ K^{-1}\ kg^{-1}$)

temperature (K)

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

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



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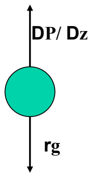
Hydrostatic Balance

What keeps air from always moving downwards due to gravity?

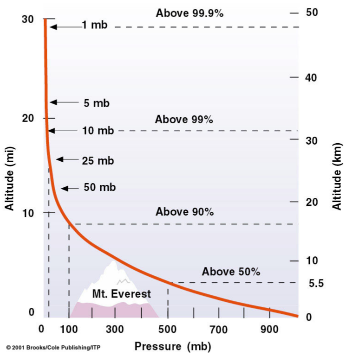
A balance between gravity and the pressure gradient force.

DP/ Dz = rg



The "pressure gradient force?"

Pushes from high to low pressure.



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Buoyancy

An air parcel rises in the atmosphere when its density is less than its surroundings

Let r_{env} be the density of the environment.

From the Ideal Gas Law

$r_{env} = P/RT_{env}$

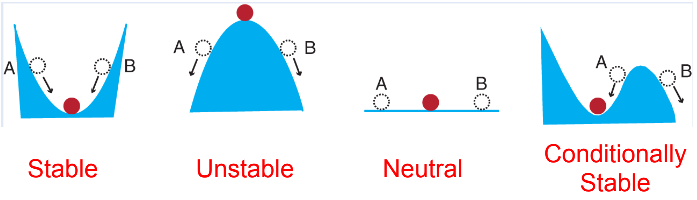
Let r_{parcel} be the density of an air parcel. Then

$r_{parcel} = P/RT_{parcel}$

Since both the parcel and the environment at the same height are at the same pressure

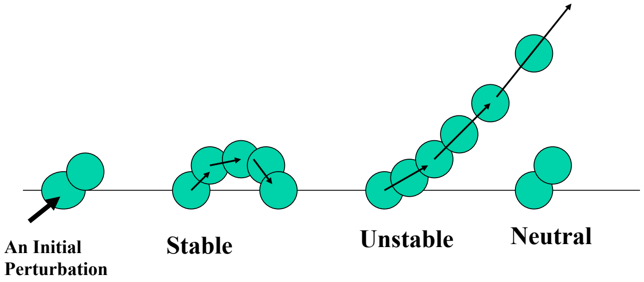
- when $T_{parcel} > T_{env}$ $r_{parcel} < r_{env}$ (positive buoyancy)
- when $T_{parcel} < T_{env}$ $r_{parcel} > r_{env}$ (negative buoyancy)

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

Why is stability important?

Vertical motions in the atmosphere are a critical part of energy transport and strongly influence the hydrologic cycle

- Without vertical motion, there would be no precipitation, no mixing of pollutants away from ground level - weather as we know it would simply not exist!
- There are two types of vertical motion:
  - forced motion such as forcing air up over a hill, over colder air, or from horizontal convergence
  - buoyant motion in which the air rises because it is less dense than its surroundings

Trading Height for Heat (cont'd)

Suppose a parcel exchanges no energy with its surroundings …

we call this state *adiabatic*, meaning, "not gaining or losing energy"

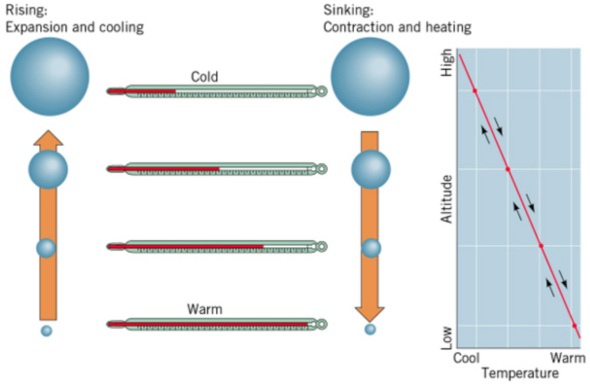
$$0 = c_p \Delta T + g \Delta z$$

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

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

"Dry lapse rate"

Dry Lapse Rate



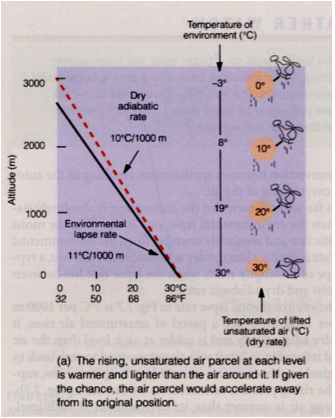
10 degrees C per kilometer

Warming and Cooling due to changing pressure

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

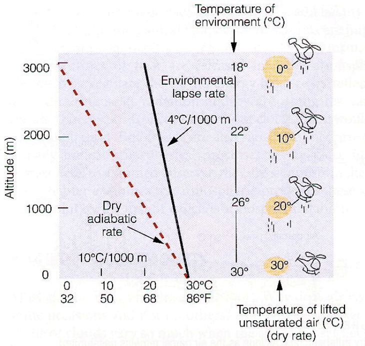


(a) The rising, unsaturated air parcel at each level is warmer and lighter than the air around it. If given the chance, the air parcel would accelerate away from its original position.

- 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

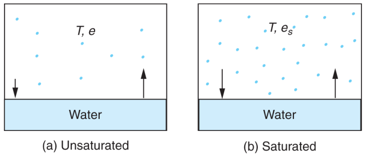
Stable Atmosphere

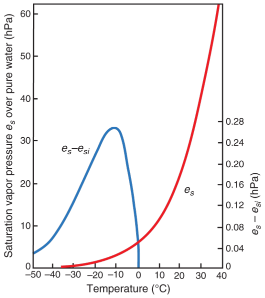
- The atmosphere is stable if the actual lapse rate is less than the dry lapse rate
 (air cools less than 10 C/km)
- This situation is common in nature (happens most calm nights, esp in winter)
  - Usually results from surface cooling and is confined to a shallow layer near the surface
  - Vertical mixing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



(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

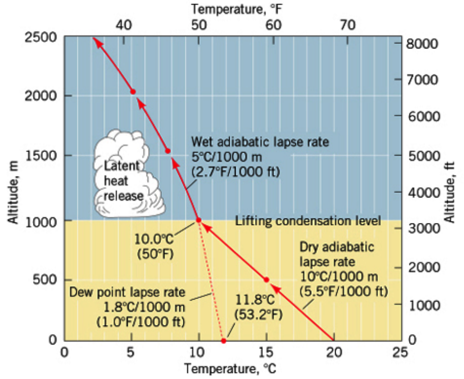
Water Vapor, Liquid Water, and Air





- Water molecules make phase transitions
- When vapor and liquid are in equilibrium, the air is "saturated"
- Saturation vapor pressure e_s depends only on temperature
- Dewpoint temperature T_d depends only on vapor pressure e

Moist Adiabatic Lapse Rate

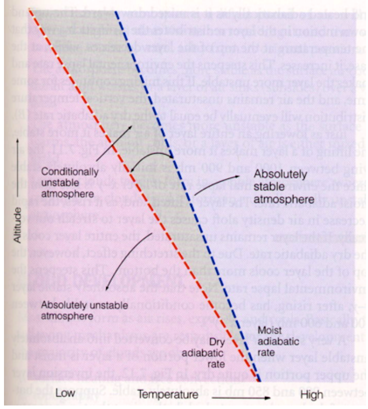


Warming and cooling due to both changes in pressure and latent heat release

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



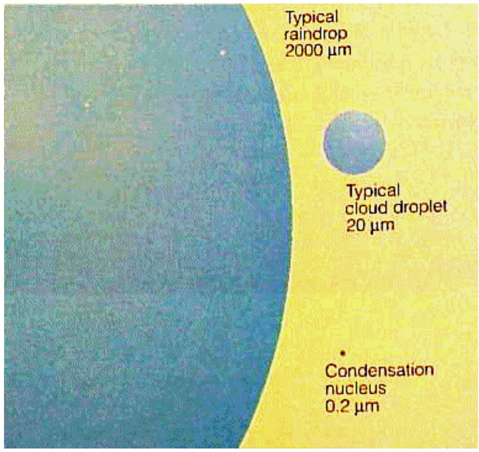
Condensation

- Phase transformation of water vapor to liquid water
- Water does not easily condense without a surface present
  - Vegetation, soil, buildings provide surface for dew and frost formation
  - Particles act as sites for cloud and fog drop formation

Cloud and fog drop formation

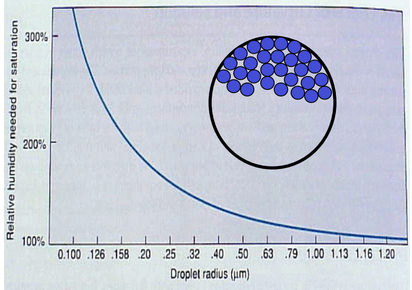
- If the air temperature cools below the dew point (RH > 100%), water vapor will tend to condense and form cloud/fog drops
- Drop formation occurs on particles known as cloud condensation nuclei (CCN)
- The most effective CCN are water soluble
- Without particles clouds would not form in the atmosphere!
  - RH of several hundred percent required for pure water drop formation

Cloud Droplets are Tiny!



Very Small Drops Evaporate!

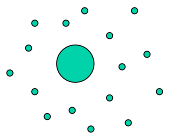
- Surface of small drops are strongly curved
- Stronger curvature produces a higher e_{sat}
- Very high RH required for equilibrium with small drops
  - ~300% RH for a 0.1 µm pure water drop



If small drops evaporate, how can we ever get large drops?!

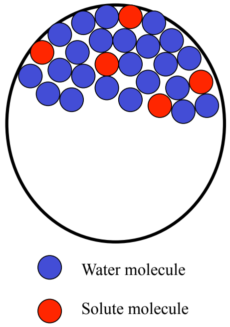
Nucleation of Cloud Droplets

- Formation of a pure water drop without a condensation nucleus is termed "homogeneous nucleation"
- Random collision of water vapor molecules can form a small drop embryo
  - Collision likelihood limits maximum embryo size to < 0.01 µm
- e_{sat} for embryo is several hundred percent
  - Embryo evaporates since environmental RH < 100.5%



Effects of Dissolved Stuff

- Condensation of water on soluble CCN dissolves particle
  - Water actually condenses on many atmospheric salt particles at RH ~70%
- Some solute particles will be present at drop surface
  - Displace water molecules
  - Reduce likelihood of water molecules escaping to vapor
  - Reduce e_{sat} from value for pure water drop



Steps in Cloud/Fog Formation

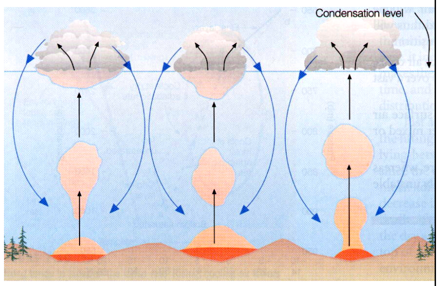
- Air parcel cools causing RH to increase
  - Radiative cooling at surface (fog)
  - Expansion in rising parcel (cloud)
- CCN (tenths of μm) take up water vapor as RH increases
  - Depends on particle size and composition
- IF RH exceeds critical value, drops are *activated* and grow readily into cloud drops (10's of μm)

Cloud Condensation Nuclei

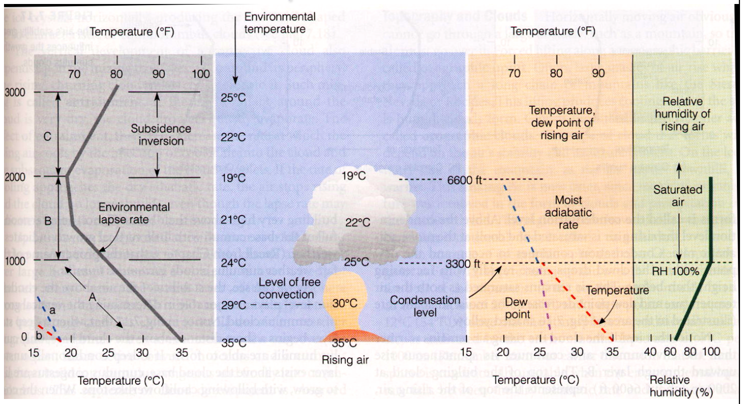
- Not all atmospheric particles are cloud condensation nuclei (CCN)
- Good CCN are hygroscopic ("like" water, in a chemical sense)
- Many hygroscopic salt and acid particles are found in the atmosphere
- Natural CCN
  - Sea salt particles (NaCl)
  - Particles produced from biogenic sulfur emissions
  - Products of vegetation burning
- CCN from human activity
  - Pollutants from fossil fuel combustion react in the atmosphere to form acids and salts

Fair weather cumulus cloud development

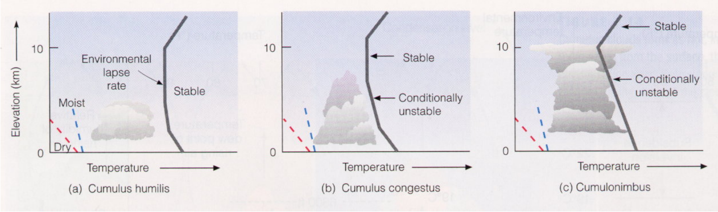
- Buoyant thermals due to surface heating
- They cool at dry adiabatic lapse rate (conserve ⊠)
- Cloud forms when $T = T_d$ (RH ~ 100%)
- Sinking air between cloud elements
- Rising is strongly suppressed at base of subsidence inversion produced from sinking motion associated with high pressure system



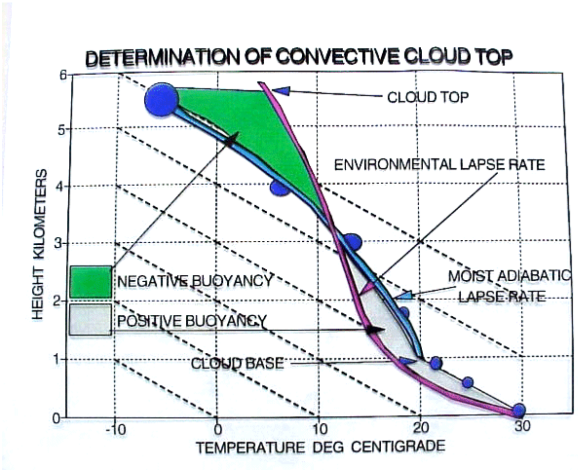
Fair weather cumulus cloud development schematic



What conditions support taller cumulus development ?

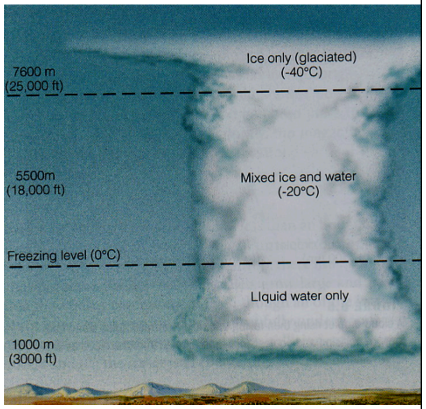


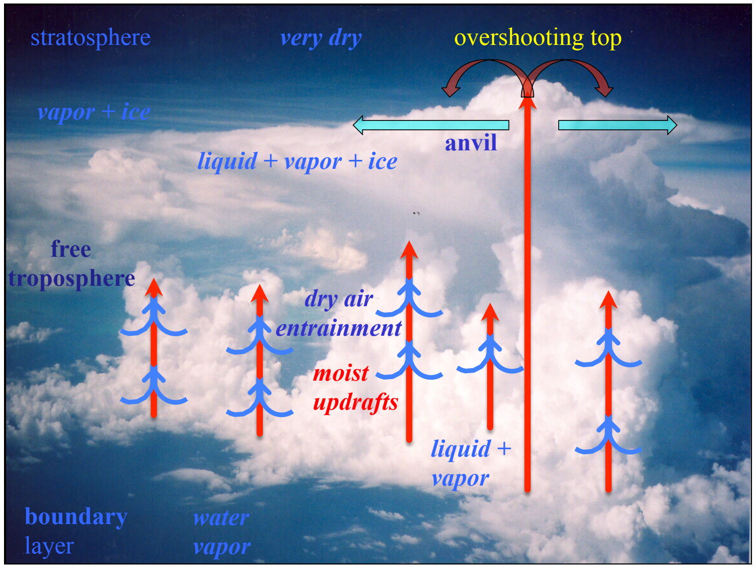
- A less stable atmospheric (steeper lapse rate) profile permits greater vertical motion
- Lots of low-level moisture permits latent heating to warm parcel, accelerating it upward

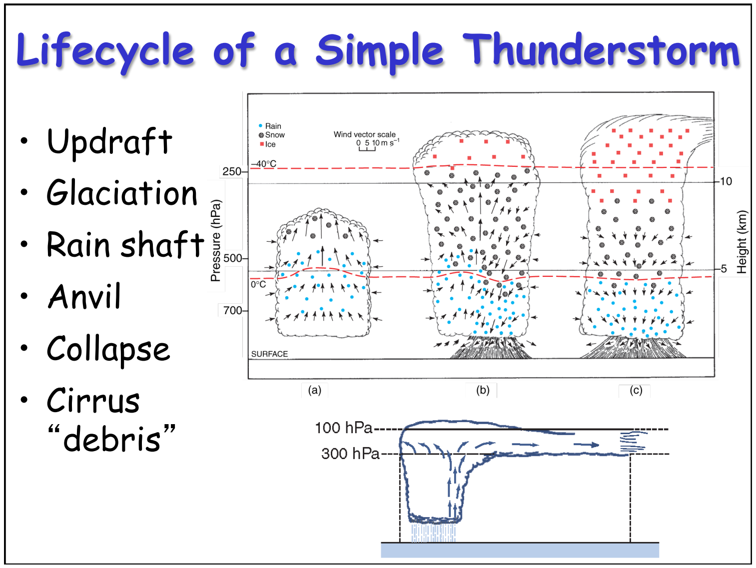


Ice Crystal Processes in Cold Clouds

- Outside deepest tropics most precipitation is formed via ice crystal growth
- *Supercooled* cloud drops and ice crystals coexist for –40° < T < 0° C
  - Lack of freezing nuclei to “glaciate” drops
- Ice crystals can grow by
  - Water vapor deposition
  - Capture of cloud drops (accretion/riming)
  - Aggregation







Lifecycle of a Simple Thunderstorm

- Updraft
- Glaciation
- Rain shaft
- Anvil
- Collapse
- Cirrus “debris”