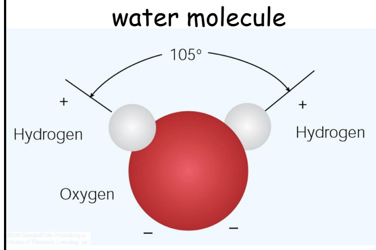
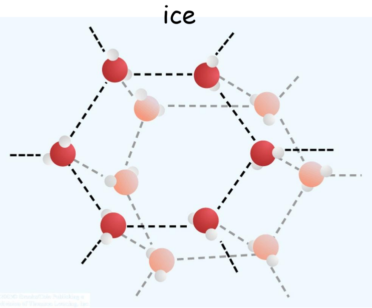
Water in the Atmosphere

Water vapor in the air
Saturation and nucleation of droplets
Moist Lapse Rate
Conditional Instability
Cloud formation and moist convection
Mixed phase clouds
(vapor, droplets, and ice)

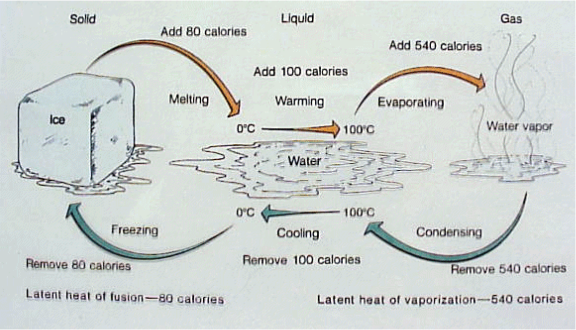
Molecular Structure of Water





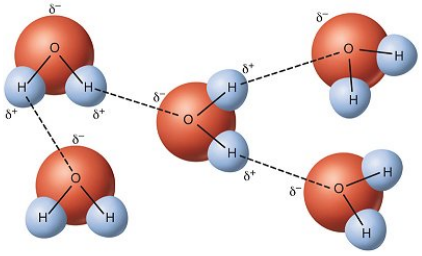
Water's unique molecular structure and hydrogen bonds enable all 3 phases to exist in earth's atmosphere.

"Latent" (hidden) Energy associated with phase changes



Why does it take so much energy to evaporate water?

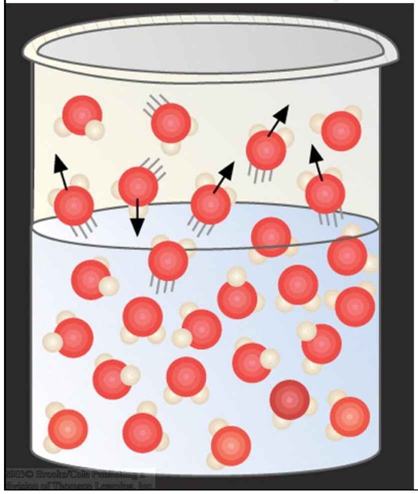
- In the liquid state, adjacent water molecules attract one another
- This same hydrogen bond accounts for surface tension on a free water surface



"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



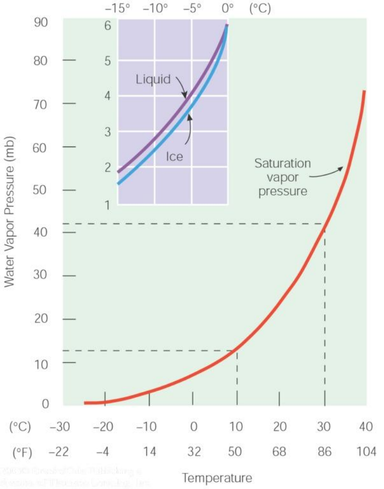
- Water molecules move between the liquid and gas phases
- When the rate of water molecules entering the liquid equals the rate leaving the liquid, we have equilibrium
  - The air is said to be saturated with water vapor at this point
  - Equilibrium does not mean no exchange occurs

Water vapor pressure

- Molecules in an air parcel all contribute to pressure
- Each subset of molecules (e.g., N_2, O_2, H_2O) exerts a partial pressure
- The VAPOR PRESSURE, is the pressure exerted by water vapor molecules in the air

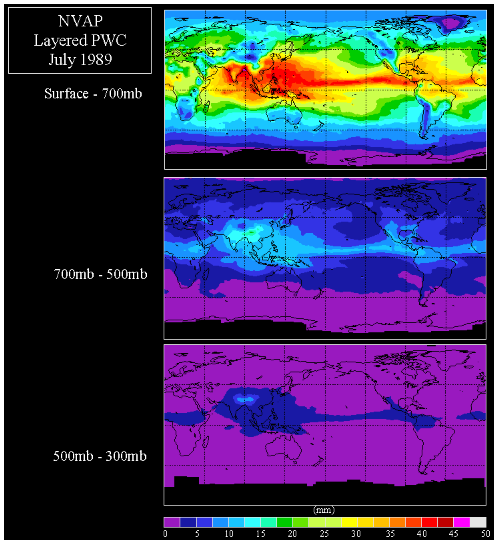
Saturation and Temperature

- 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*"
- There is also a vapor pressure of water over an ice surface
  - The saturation vapor pressure above solid ice is less than above liquid water



Water vapor is not evenly distributed throughout the atmosphere

- Generally largest amounts are found close to the surface (where it's warm), decreasing aloft (where it's cold)
  - Closest to the source - evaporation from ground, plants, lakes and ocean
  - Warmer air can hold more water vapor than colder air



"Relative Humidity"

- Relative Humidity (RH) is the amount of water vapor in the air divided by the amount it could hold, expressed as a percentage:
  - 100 x (actual vapor pressure) / (saturation vapor pressure)
  - Air with RH > 100% is called "supersaturated"
- Relative humidity depends on BOTH
  - Changes in water vapor pressure (numerator)
  - Changes in temperature, which changes saturation vapor pressure (denominator)

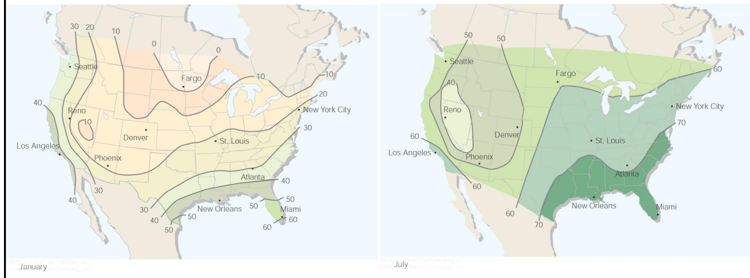
Other ways to express the amount of water vapor air

- Absolute humidity
  - mass of water vapor/volume of air (g/m^3)
  - *changes when air parcel volume changes*
- Mixing ratio
  - mass of water vapor/mass of dry air (g/kg)
- **Dew point temperature: the temperature to which the air could be chilled before dew condenses**
- **"Better" than RH because it's an unambiguous measure of water vapor (doesn't depend on T)**

Dew

- Surfaces cool strongly at night by radiative cooling
  - Strongest on clear, calm nights
- The *dew point* is the temperature at which the air is saturated with water vapor
- If a surface cools below the dew point, water condenses on the surface and dew drops are formed
- Dew does not "fall"

Dewpoint Temperatures



- If air cools to its dewpoint, then dew will form
- Dewpoint is a measure of the water vapor content
- It is not a measure of temperature!

Which environment has higher water vapor content?

(a) POLAR AIR: Air temperature –2°C
Dew point –2°C
Relative humidity 100 percent

(b) DESERT AIR: Air temperature 35°C
Dew point 5°C
Relative humidity 16 percent

FIGURE 5.14
The polar air has the higher relative humidity, whereas the desert air, with the higher dew point, contains more water vapor.

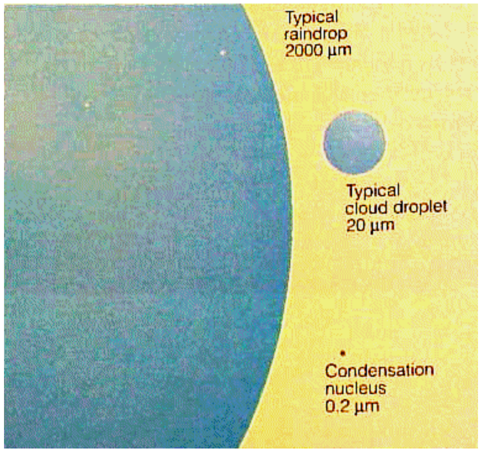
Condensation

- 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 in the air (like smoke or dust) 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!

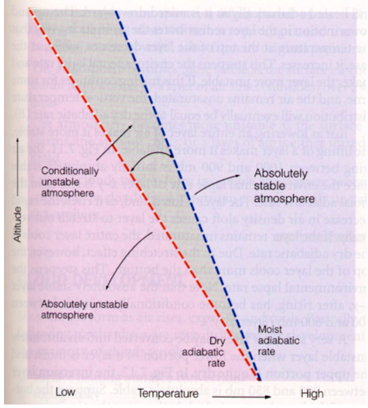


Saturated Rising Air Cools Less Than Dry Air!

- If a rising air parcel becomes saturated condensation occurs
- Condensation warms the air parcel due to the release of latent heat
- So, a rising parcel cools less if it is saturated
- Define a moist lapse rate
  - around 6 °C per km
  - Not constant (varies from ~ 3-9 °C)
  - depends on T and P

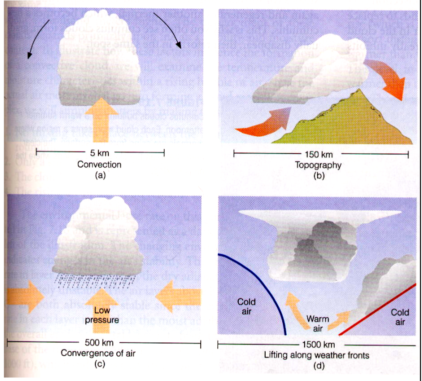
Conditionally unstable air

- 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



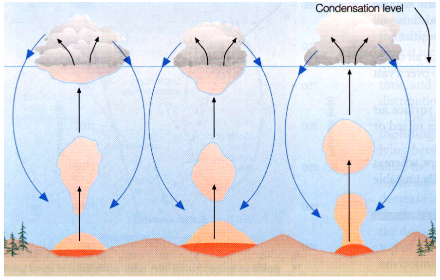
Cloud development

- Clouds form as air rises, expands and cools
- Most clouds form by
  - Surface heating and free convection
  - Lifting of air over topography
  - Widespread air lifting due to surface convergence
  - Lifting along weather fronts



Fair-Weather Cumulus Clouds

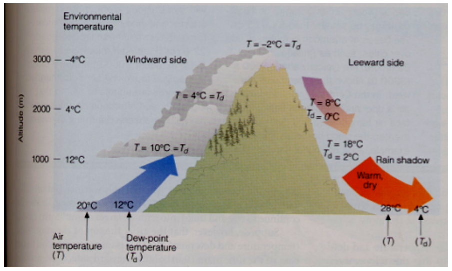
- Air rises due to surface heating
- RH rises as rising parcel cools
- Clouds form at RH ~ 100%



- Rising is strongly suppressed at base of subsidence inversion produced from sinking motion associated with high pressure system
- Sinking air is found between cloud elements

Mountain (Orographic) Clouds

- Forced lifting along a topographic barrier causes air parcel expansion and cooling
- Clouds and precipitation often develop on upwind side of obstacle
- Air dries further during descent on downwind side

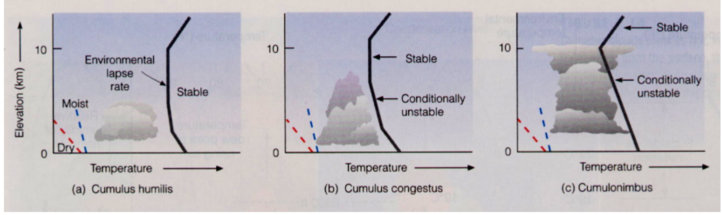


How Tall Do they Get?

Cloud tops are defined by how far a rising air parcel can go before it's colder than its surroundings

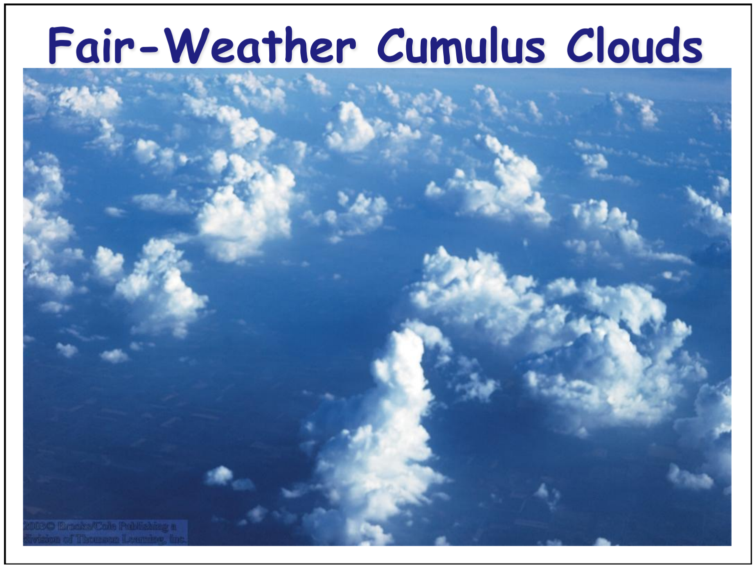
- **Rising air cools until it reaches its dewpoint**
- **Condensation of cloud droplets warm the air so that it becomes more buoyant (warmer than its clear surroundings)**
- **Cloudy air accelerates upward until it reaches a layer in which it's cooler than its surroundings, but by then it's rising fast!**
- **Cloud begins to decelerate but still rises until it runs out of upward momentum**

Why Do Some Clouds Get Really Big?

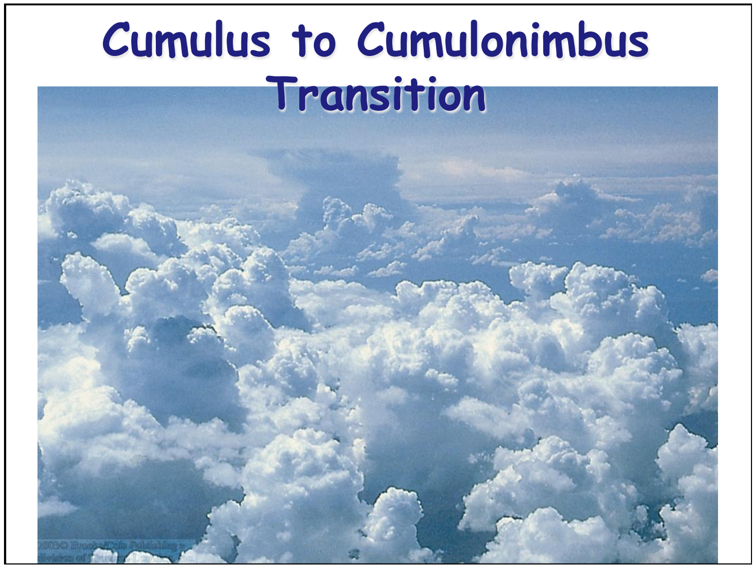


(a) Cumulus humilis (b) Cumulus congestus (c) Cumulonimbus

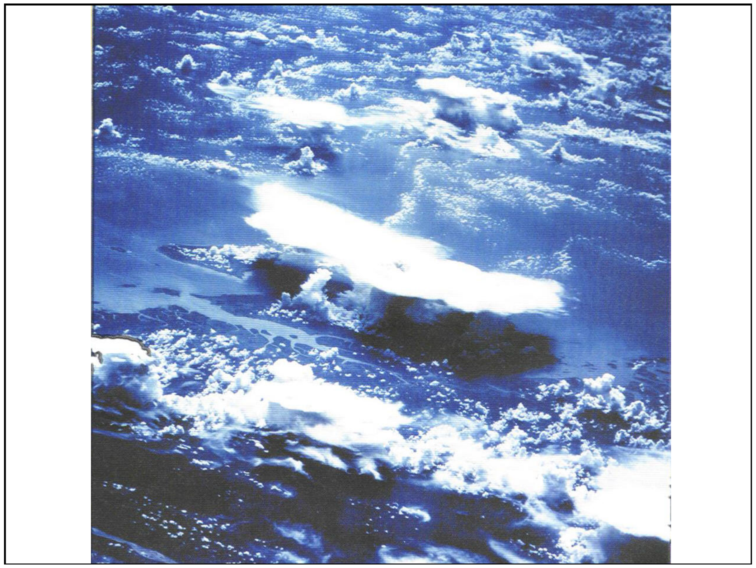
- A less stable atmospheric (steeper lapse rate) profile permits greater vertical motion
- Lots of low-level moisture permits latent heating to warm parcel, accelerating it upward



Fair-Weather Cumulus Clouds



Cumulus to Cumulonimbus Transition

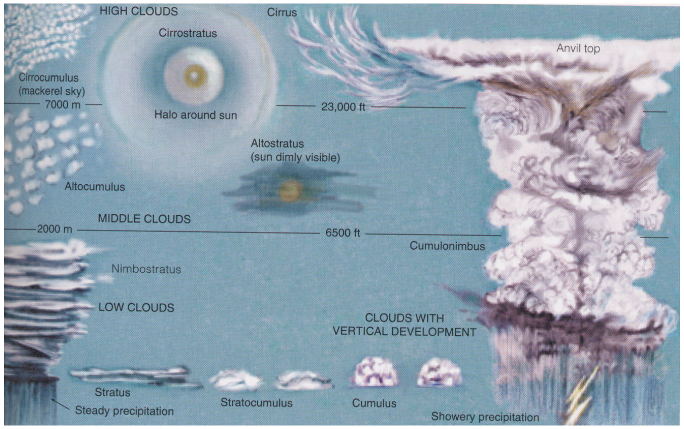


Cloud Classification

Clouds are categorized by their height, appearance and vertical development

- High Clouds - generally above 16,000 ft at middle latitudes
  - **Cirrus, Cirrostratus, Cirrocumulus**
- Middle Clouds – 7,000-23,000 feet
  - **Altostratus, Altocumulus**
- Low Clouds - below 7,000 ft
  - **Stratus, stratocumulus, nimbostratus**
- Vertically “developed” clouds (via convection)
  - **Cumulus, Cumulonimbus**

Cloud Type Summary

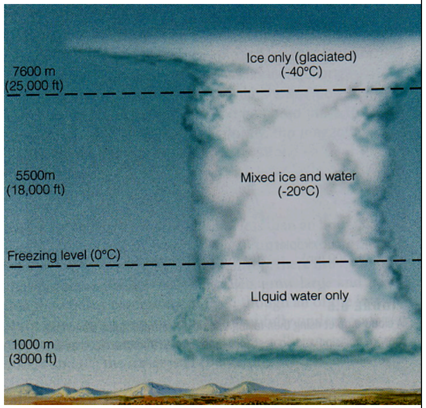


Cirrus

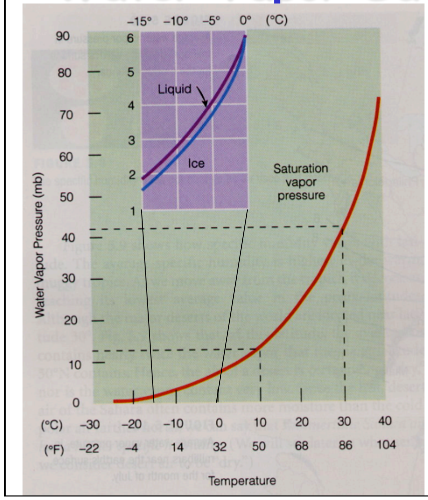
Stratiform cloud layers

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



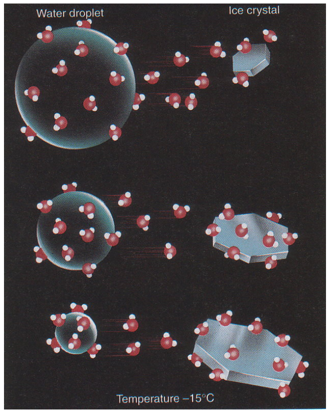
Water Vapor Saturation vs T



- Saturation vapor pressure over ice is less than that over liquid water at a given temperature
- In mixed-phase clouds, liquid water can evaporate even as vapor is deposited onto ice

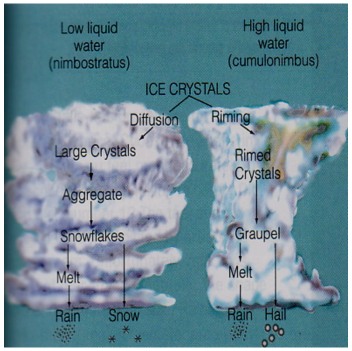
Ice Crystal Growth by Direct Vapor Deposition

- Ice binds water molecules more tightly than liquid water
- This leads to evaporation of water from supercooled cloud drops and deposition onto ice crystals
- Ice crystals grow at the expense of liquid droplets

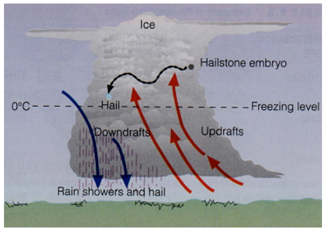


Precipitation in cold clouds

- Low liquid water content promotes diffusion/ deposition growth of large crystals
- High liquid water content promotes riming and formation of graupel/hail
- If the sub-cloud layer is warm, snow or graupel may melt into raindrops before reaching the surface (typical process for summer rain in Colorado)



Hail



- Hail can form in clouds with
  - High supercooled liquid water content
  - Very strong updrafts
- Hailstones associated with deep and intense cumulonimbus
  - Typically make 2-3 trips up through cloud
- Opaque and clear ice layers form
  - Opaque represents rapid freezing of accreted drops
  - Clear represents slower freezing during higher water accretion rates
  - Layering tells about hailstone history

The largest hailstone ever recovered in the United States, a seven-inch (17.8-centimeter) wide chunk of ice almost as large as a soccer ball. It was found in Aurora, Nebraska on June 22, 2003. The hailstone lost nearly half of its mass upon landing on the rain gutter of a house