Clouds and Precipitation

Lifting, condensation, and cloud development

Deep convective clouds (thunderstorms)

Types of clouds and how they form

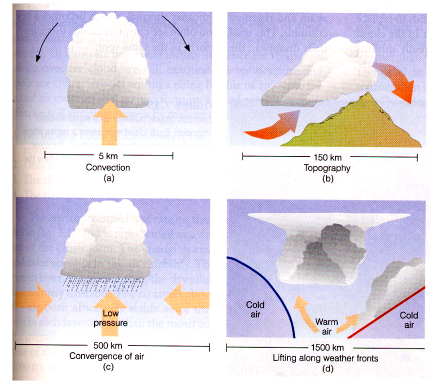
Collision and coalescence of raindrops

Crucial roles of ice in most precipitation

Cloud Development

Most clouds form by

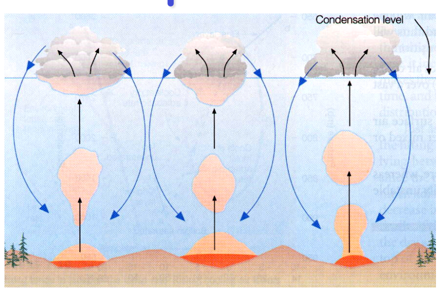
- Surface heating and free convection
- Lifting of air over topography
- Widespread air lifting due to surface convergence
- Lifting along weather fronts



Clouds form as air rises, expands and cools

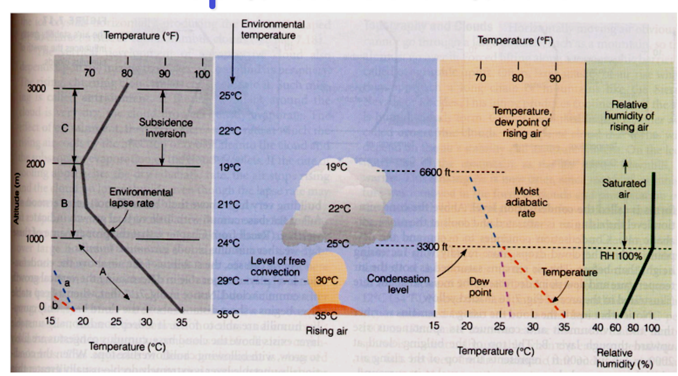
Fair-Weather Cumulus Cloud Development

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

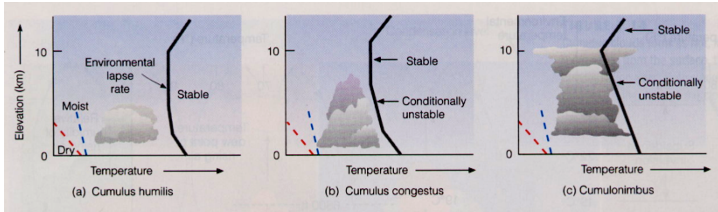


- Rising is strongly suppressed at base of subsidence inversion produced from sinking motion aloft
- Sinking air is found between cloud elements

Fair weather cumulus cloud development schematic



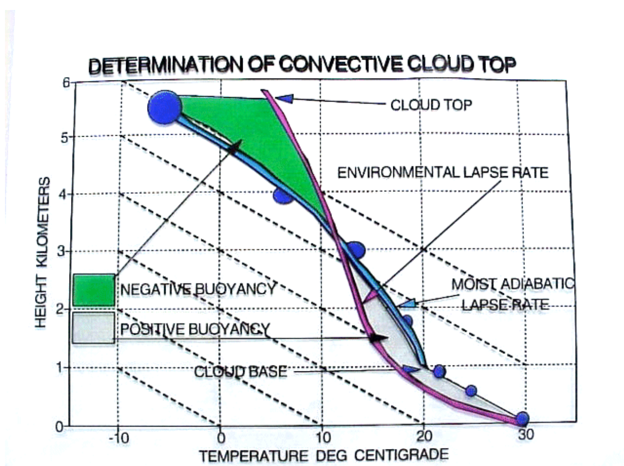
Why Do Some Clouds Get Really Big?



- 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

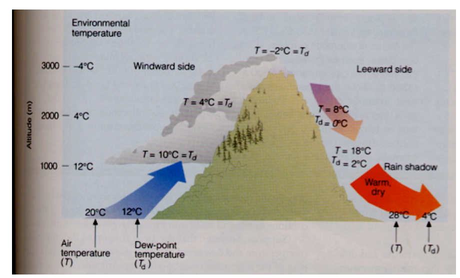
How Tall Do they Get?

- **Cloud top is defined by the upper limit to air parcel rise**
- **The area between the dry/moist adiabatic lapse rate, showing an air parcel's temperature during ascent, and the environmental lapse rate, can be divided into two parts**
  - A positive acceleration part where the parcel is warmer than the environment
  - A negative acceleration part where the parcel is colder than the environment
- **The approximate cloud top height will be that altitude where the negative acceleration area is equal to the positive acceleration area**



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



Lenticular Clouds

- Stable air flowing over a mountain range often forms a series of waves
  - Like water waves formed downstream of a submerged boulder
- Air cools during rising portion of wave and warms during descent
- Clouds form near crests of waves
- A large swirling eddy (rotor) sometimes forms beneath the lee wave cloud (dangerous for aircraft)

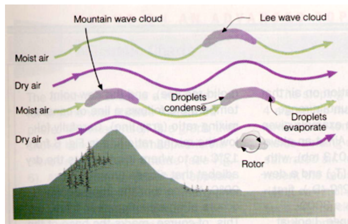
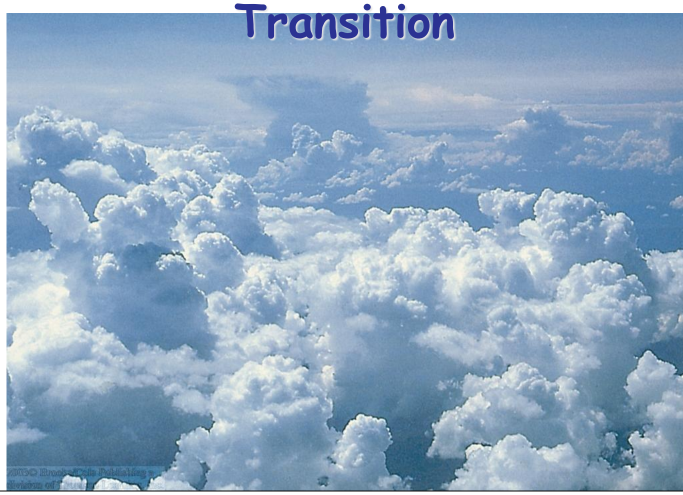
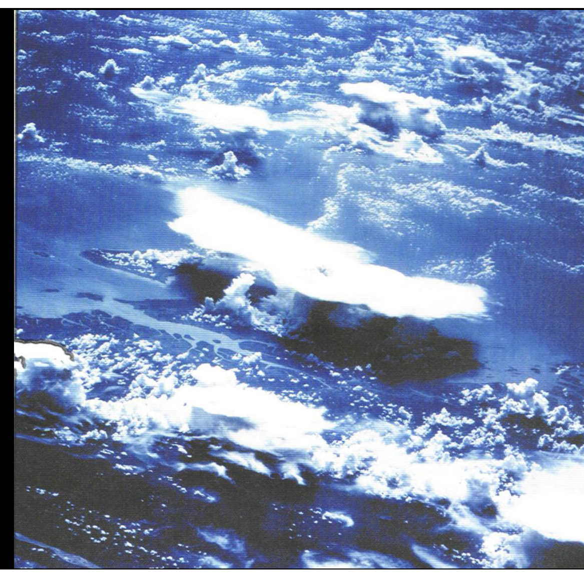


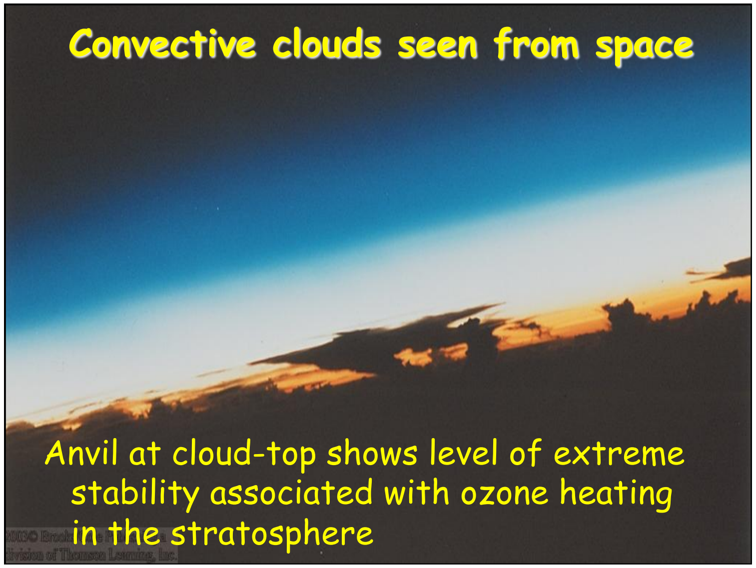
FIGURE 7.21
The formation of lenticular clouds.

Fair-Weather Cumulus Clouds

Cumulus to Cumulonimbus Transition





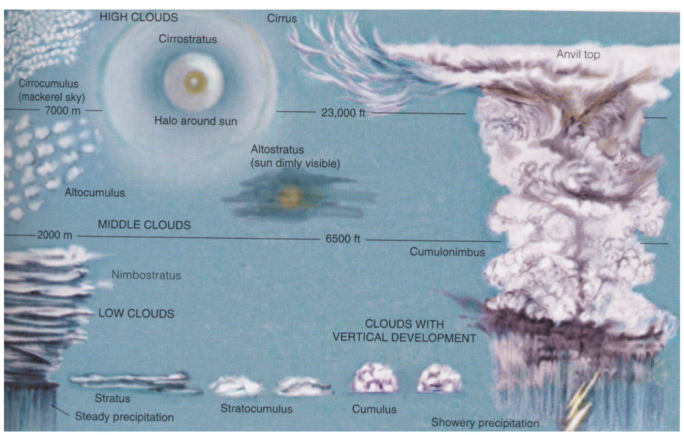


Cloud Classification

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

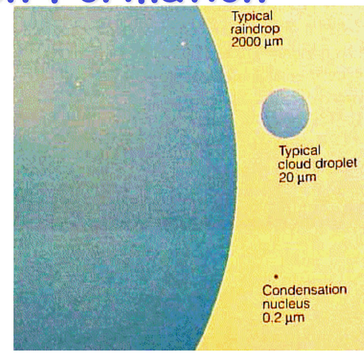
Precipitation Formation

How many 20 μm cloud drops does it take to make a single 2000 μm rain drop?

$$V = 4/3\pi r^3$$

$$V_{raindrop}/V_{cloud\text{-}drop} = (r_{raindrop}/r_{cloud\text{-}drop})^3 = (100)^3$$

~ 1 million!

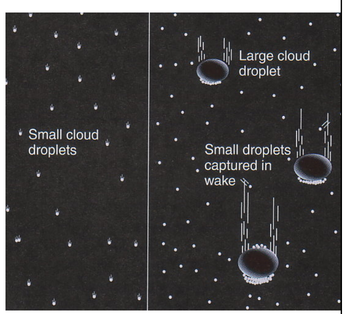


How does precipitation form from tiny cloud drops?

1. Warm rain processes (collision and coalescence)
2. The Bergeron (ice crystal) process
3. "Ice multiplication"

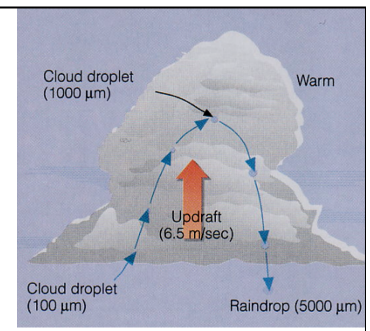
Rain Formation in Warm (not frozen) Clouds

- In a supersaturated environment, activated cloud drops grow by water vapor condensation
  - It takes many, many hours for the cloud drop to approach rain drop size
- Collisions between cloud drops can produce large rain drops much faster through coalescence
  - Collisions occur due to different settling rates of large and small drops
  - Not all collisions result in coalescence
- Warm rain formation favored by:
  - Wide range of drop sizes (big drops overtake small ones)
  - Thick cloud (more chances for collisions)
  - Fast updrafts



Rain formation in warm clouds

- Capture of a cloud/rain drop in a cloud updraft can give it more time to grow
  - The drop falls at a fixed speed relative to the air, not the ground
  - Large drops fall faster



DIAMETER (μm)	TERMINAL VELOCITY m/sec	TERMINAL VELOCITY ft/sec	TYPE OF PARTICLE
0.2	0.0000001	0.0000003	Condensation nuclei
20	0.01	0.03	Typical cloud droplet
100	0.27	0.9	Large cloud droplet
200	0.70	2.3	Large cloud droplet or drizzle
1000	4.0	13.1	Small raindrop
2000	6.5	21.4	Typical raindrop
5000	9.0	29.5	Large raindrop

Rain Drop Size and Shape

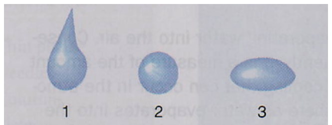
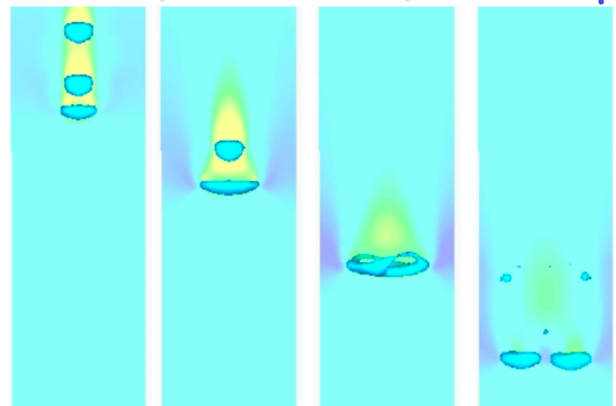


FIGURE 1
Which of the three drops drawn here represents the real shape of a falling raindrop?

- Drizzle drops – 100's of μm
- Rain drops – a few millimeters
  - Rain drops larger than 5 mm tend to break up
    - When colliding with other drops
    - From internal oscillations
- Rain drops have shapes ranging from spherical (small drops) to flattened spheroids (large drops)
  - In large drops surface tension is no longer strong enough to overcome flattening of falling drop due to pressure effects

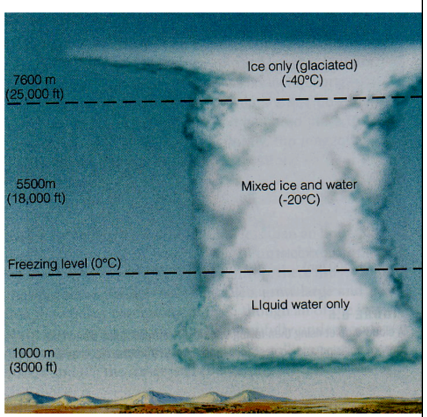
Collision, Coalescence, & Breakup



(High-resolution hydrodynamic simulation)

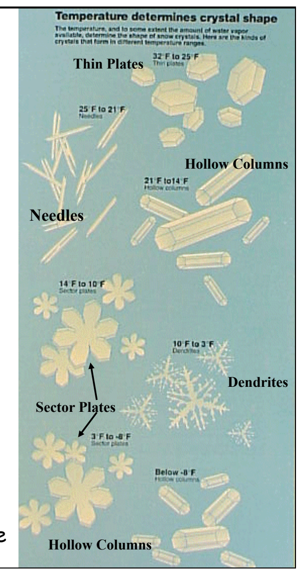
Ice Crystal Processes in Cold Clouds

- 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

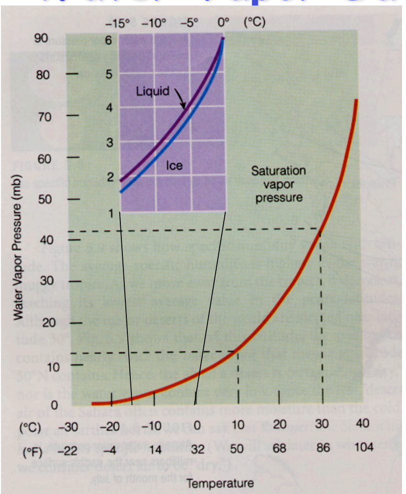


Ice Crystals and Ice Nuclei

- Ice crystal shapes depend on the environmental temperature and vapor pressure
- Ice crystal formation usually involves ice nuclei
- Ice nuclei
  - Are much less common than cloud condensation nuclei
  - Include some clay mineral particles, bacteria and plant leaf detritus
  - Initiate the freezing of water droplets at temperatures between 0°C and -40°C
  - Artificial ice nuclei, used for cloud seeding, include dry ice and silver iodide



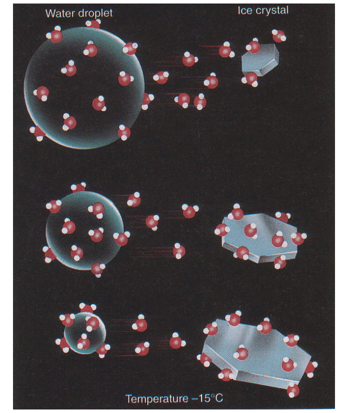
Water Vapor Saturation vs T



- 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

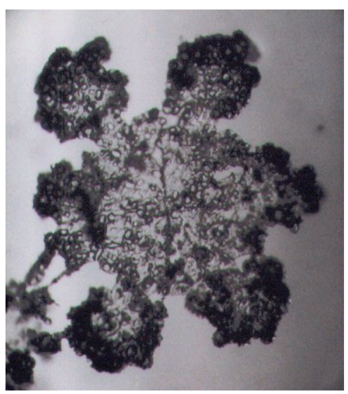
Ice Crystal Growth by Direct Vapor Deposition

- 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



Ice Crystal Growth by Accretion

- Large ice crystals fall faster than smaller liquid droplets
- Crystal/drop collisions allow ice crystals to capture cloud drops
  - The supercooled drops freeze upon contact with the ice crystal
  - This process is known as accretion or riming
- Extreme crystal riming leads to the formation of
  - Graupel
  - Hail

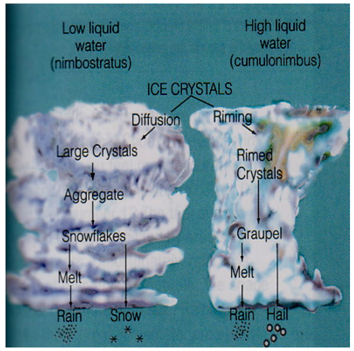


Ice Crystal Growth by Aggregation

- Crystal/crystal collisions can lead to formation of crystal aggregates
  - Crystals most likely to stick when a liquid water layer resides on the crystal surface
- Watch for large aggregates/snowflakes when temperatures are close to 0° C

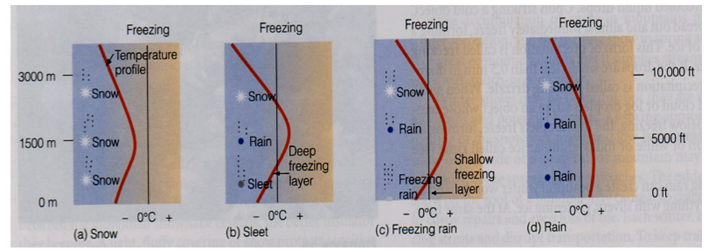
Precipitation in cold clouds

- 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)



Precipitation types

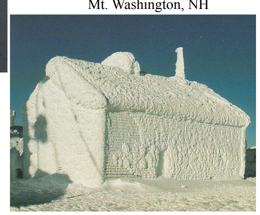
- Rain that evaporates before reaching the surface is termed *virga*
  - Common in our dry climate
- Precipitation reaching the surface can take on different forms depending on the vertical temperature profile



Freezing rain and riming

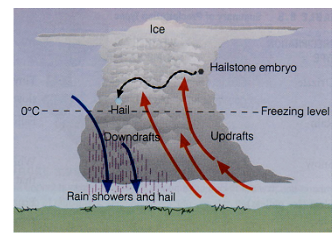
- Freezing rain coats surfaces with large quantities of ice
  - Trees break, power lines fall, roads are treacherous
- Supercooled cloud drops collected by trees (or other structures) are known as rime
- Collection of supercooled rain and cloud drops poses a hazard in the form of aircraft icing

Mt. Washington, NH



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