Chapter 7: Precipitation

The size of cloud droplets and raindrops
Increased saturation vapor pressure around a curved surface: curvature effect
Terminal velocity of droplets of various sizes
Growth of cloud droplets to rain drops by collision-coalescence
Formation of ice in the atmosphere
Growth of ice crystals via the ice-crystal process
Rain from ice
Ice: different shapes at different temperatures
Measuring precipitation

Precipitation (p. 164, column 1)

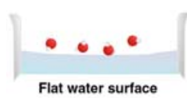
- Is it ever too cold to snow?
  No, but little snow when it is very cold for 2 reasons:
  - Capacity for water vapor is small at low temperatures, so even saturated air can condense little moisture.
  - Coldest temperatures occur when skies are clear. (Clouds are "greenhouse" blankets.)
- Is it ever too warm to snow? Snow flakes possible with surface temperature at 50° F. See p. 177.
- Precipitation = any form of water (solid or liquid) that falls from a cloud and reaches the ground, including rain, drizzle, sleet, snow, snow grains, snow pellets, ice pellets, and hail. (Precip types on pp. 174-184).

How Do Cloud Droplets Grow? (p. 164)

- Formation of raindrops from cloud droplets is complex
- Typical condensation nucleus: 0.2 micrometers
  Typical cloud droplet: 20 micrometers
  Typical rain droplet: 2000 micrometers = 2 mm
  (See fig 7.1, p. 164)
- Rain droplet radius is about 100 times greater than cloud droplet radius, so volume is about 100x100x100 = 1 million times greater
- How can cloud droplets become raindrops with a million times the volume in a few tens of minutes?
- We'll see they grow not by continued condensation but by many small droplets merging to form a rain drop.
- First, we'll consider small droplets.

Saturation around a cloud droplet

- Curvature effect: water evaporates more easily from a tiny droplet than from a flat surface because a molecule on the surface of a droplet has fewer neighboring water molecules in the liquid to hold it. (See next slide.)
- Thus, saturation vapor pressure is higher around tiny cloud droplets than over pan of water. Note the larger number of water molecules (shown in red) around the droplet than above the flat water surface. (The difference is exaggerated.)



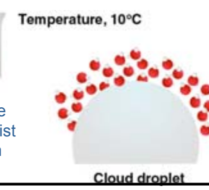
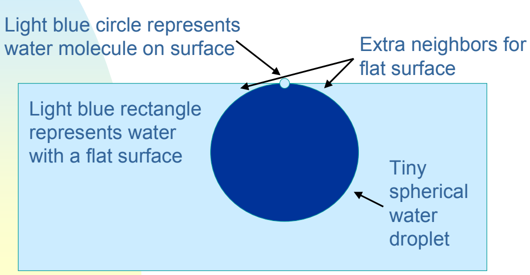


Fig. 7.2, p.165: Red balls indicate water vapor molecules. More exist around curved cloud droplet than over flat surface at saturation.

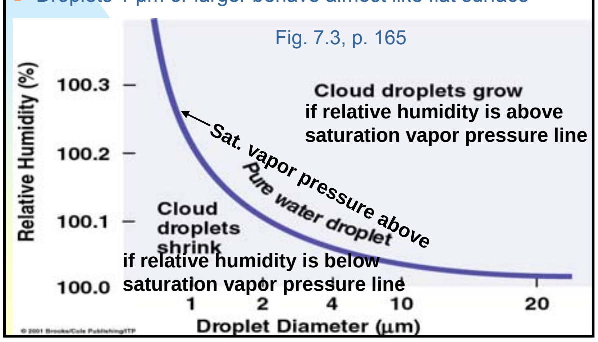
Saturation around a cloud droplet

- Compare the number of neighboring molecules for a molecule on a flat surface versus the number of neighbors when the surface is curved. (Figure below not in textbook.)



Saturation around a droplet (p. 165)

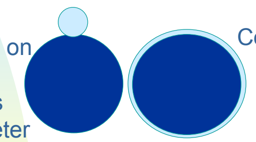
- Saturation vapor pressure is largest for smallest droplets
- Droplets 1 μm or larger behave almost like flat surface



Wettable vs unwettable (hydrophobic) condensation nuclei

- Imagine wettable and unwettable condensation nuclei side by side. Suppose that roughly the same amount of water condenses on each one.

Condensation on unwettable nucleus has small diameter



Condensation on wettable nucleus has large diameter

- Condensation drop on unwettable nucleus has small diameter. => High sat vapor pressure => more evap.
- Condensation spreads over entire wettable nucleus; large diam. => Lower sat vapor pressure => less evap.

Therefore …

- Condensation on a large diameter, wettable nucleus evaporates less easily than from a tiny droplet on an unwettable (hydrophobic) nucleus because of less curvature.
- Analogy to cultured pearls: Cultured pearls are made by inserting a spherical “seed” (made from shell) into an oyster. The seed is almost as big as the desired pearl. The oyster does not have to deposit much onto the seed to produce what appears to be a large pearl. If water condenses onto a large wettable condensation nucleus, it “appears” to be a large droplet, which does not evaporate as easily because its surface is flatter.

Solute Effect (p. 165, column 1)

- Some substances (like salt, NaCl) are hygroscopic, i.e., water can condense on them at less than 100% relative humidity. Here is why.
- When water condenses onto hygroscopic material, the hygroscopic material dissolves, forming a solution (like salt water). The molecules in the solution (like salt ions, Na^+ and Cl^-) bind closely with water, inhibiting evaporation. Known as **solute effect**.
- Curvature effect, which raises humidity needed for condensation, and solute effect, which lowers humidity needed for condensation, roughly cancel each other. Most condensation in the air occurs around 100% relative humidity.

How fast does a water droplet fall? Terminal velocity (p. 166)

- Terminal velocity = maximum speed of falling body.
  - Force of gravity downward balances air resistance up.
  - Larger drops fall faster than smaller drops.
  - Terminal velocity (Table 7.1, p. 166)
    - Condensation nucleus (0.2 um): essentially 0 m/s
    - Cloud droplet (20 um): 0.01 m/s = 1 cm/s
    - Small rain droplet (1 mm): 4 m/s
- Similar principle for things that rise buoyantly, e.g., a weather balloon rises at its terminal velocity. Its upward buoyancy force is balanced by air resistance, so it rises at a steady rate.

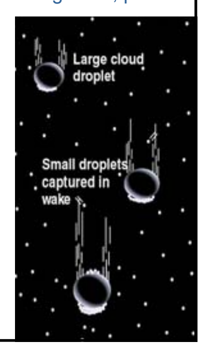
Terminal velocity of a person

- In the troposphere, the terminal velocity of a person without a parachute is about 100 mph.
- In 1960, US Air Force Capt Joseph Kittinger jumped out of a balloon at 102,000 feet with parachute. Because air is so thin at that altitude, he reached about 600 mph before his parachute slowed him. See http://hypertextbook.com/facts/JianHuang.shtml
- In 1972, a DC-9 over Czechoslovakia exploded at 33,360 feet from a Croat terrorist bomb. Yugoslav stewardess Vesna Vulovic, strapped in her seat, survived the plane’s fall onto a snow-covered mountainside. She was the only survivor. She fractured skull, broke 3 vertebra & both legs, was in coma for 3 days, & temporarily paralyzed from waist down but made full recovery.

Forming a rain drop in a cloud without ice: Falling droplets collide (pp. 166-167)

- Larger droplets fall faster and collide with smaller droplets
- If there is big difference between size of falling droplet and droplet it nears, small droplet may be swept to the side & not collide. (Just as not every bug in front of your car hits the windshield.)
- A few of the droplets that are swept to the side swirl back in the big droplet’s wake & hit it on the back.
- Example: Of 100 droplets in the path of a bigger droplet, 80 may hit it directly, and 20 are swept aside. Of the 20 swept aside, 4 may collide by “wake capture.” Total: 84% collisions.

Fig. 7.4b, p. 166



Coalescence of droplets that collide pp. 166-167

- Collision of 2 droplets does not guarantee that the droplets will merge ("coalesce"). Coalescence more likely when droplets have opposite electrical charge. (Opposites attract.)
- The tiniest cloud droplets have so much surface tension that they may bounce apart when they collide.
- Continuing the example from previous slide, if 84 out of 100 droplets collide with a bigger droplet, maybe 63 will coalesce with it. So roughly 63% of droplets will collide and coalesce.
- Collision and coalescence can combine cloud droplets to make rain drops. The thicker the cloud & the faster the rising air in the cloud, the longer a raindrop spends in a cloud & the bigger the drop gets. Biggest drops are from thunderstorms (up to 5 mm); smallest from stratus clouds (0.2 mm – 0.5 mm: drizzle).
- Biggest raindrops are torn apart directly by collisions and by oscillations (vibrations) caused by collisions.

Formation of ice in the atmosphere (p. 167-168)

- If water freezes in the atmosphere, it needs to freeze *onto* something to build an ice crystal.
- Ice nucleus = particle on which freezing occurs
  - Not abundant
  - Ice is the best ice nucleus
  - Clay dust is most common; effective below −15°C
- Water in air warmer than −10°C (14°F) is rarely frozen
- Without ice nuclei, the temperature must be almost −40°C (−40°F) for all water to be frozen
- At temperatures between −10°C and −40°C, there is a mix of liquid droplets and ice crystals

Types of ice nuclei (p. 168)

- Don't memorize all the processes below. Just remember that there are various ways to make ice in the atmosphere.
- Deposition nuclei: particles on which water vapor can "deposit" directly as ice (no liquid).
- Freezing nuclei: particles that will freeze supercooled water, i.e., liquid water with temperature below 0°C = 32°F. Some freezing nuclei cause freezing when they:
  - are immersed in liquid water
  - promote condensation, then freezing
  - collide with supercooled liquid water (contact freezing)

Saturation vapor pressure over ice is less than over liquid water (p. 169)

- Ice is a crystal. Liquid water is more disorganized.
- Molecules are bound more tightly in ice than in liquid.
- So it takes more energy for water to evaporate from ice than from liquid. Therefore, the saturation vapor pressure is lower above ice than above liquid water.

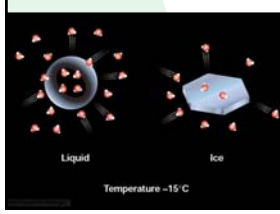
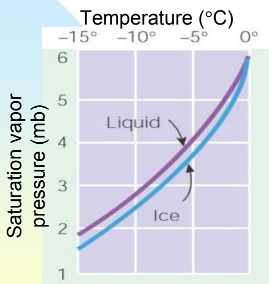


Fig. 7.7, p. 169 Water evaporates more easily from liquid than from ice, so greater saturation vapor pressure around liquid than ice. This figure exaggerates the difference.

Difference between saturation vapor pressure over liquid and ice



Insert from Fig. 4.10, p. 91: Saturation vapor pressure over liquid water and over ice

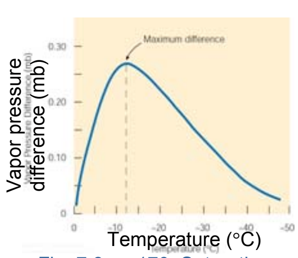
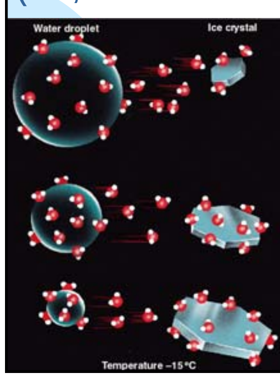


Fig. 7.8, p. 170: Saturation vapor pressure over liquid water minus saturation vapor pressure over ice

Ice-crystal process in "cold" clouds (i.e., clouds with ice, p. 170 – 171)



- Ice crystal process: With both liquid and ice present, liquid evaporates, & ice grows
- Most effective with 100,000 to 1,000,000 droplets for each ice crystal. If too many ice particles, ice crystals are too small to fall, and cloud is converted to cirrus without precipitation.

History of precipitation theories

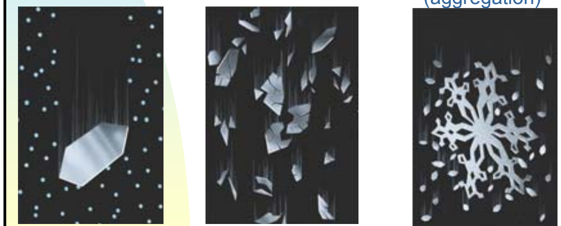
- Theory of ice-crystal process, also called Wegener-Bergeron-Findeisen process, preceded collision-coalescence theory because ice-crystal process is important in mid-latitudes where most meteorologists live.
- German Alfred Wegener proposed "ice-crystal process" theory in 1911 book "Thermodynamics of the Atmosphere" but is more famous for 1910 theory of continental drift. (p. 171)
- In 1922, Swede Tor Bergeron realized the significance of this process while taking walks through fog (*Bulletin of American Meteorological Society*, May 1979, p. 408). Bergeron and Walter Findeisen (German) added to theory in 1930's.
- The collision-coalescence theory was proposed after pilots in World War II (1940's) reported rain from tropical clouds with no ice.

Falling ice crystals can ... (Fig. 7.10, p. 171)

Grow as they hit supercooled droplets that freeze to them (accretion)

Shatter as they hit other ice crystals, creating more ice nuclei

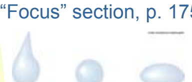
Collide with other ice crystals that stick and augment the crystals to make snowflakes (aggregation)



Explanatory text: p. 170.

Rain from melted ice crystals

- Most rain in midlatitudes starts as ice by means of the "ice crystal process" and melts as it falls. See fig. 7.13, p. 173.
- Cloud seeding: inject ice nuclei into cloud to encourage ice crystal process. First attempts in 1940's used dry ice (-78°C) to initiate freezing. In 1947, Bernard Vonnegut, brother of author Kurt Vonnegut, was first to inject silver iodide particles (easier to handle than dry ice) to function as ice nuclei (pp. 171-172).
- In general, rain drops are not tear shaped. Small rain drops are round. Larger drops are flattened on the bottom by air resistance. See "Focus" section, p. 175.



No! Small (< 2 mm) Large (> 2 mm)

Ice freezes into different shapes

- Water freezes into different shapes at different temperatures. (Look at table 7.3, p. 176, but don't memorize it.)

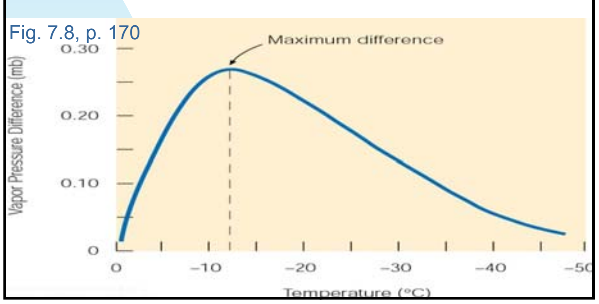
Fig. 7.16, p. 176: Common forms of ice crystals

Dendrite = 6-sided snowflake

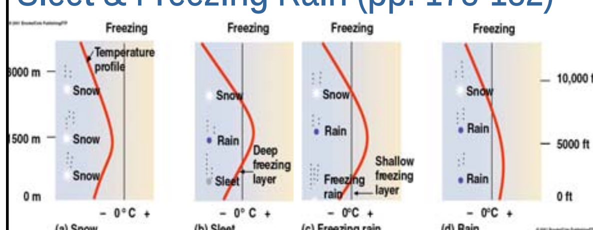
Why are 6-sided snowflakes more abundant than other ice shapes? (p. 176)

-12 to -16°C is the range for 6-sided snowflakes (dendrites) & for the max. diff. between saturation vapor pressure over liquid and ice. Therefore, 6-sided snowflakes form most rapidly.

Fig. 7.8, p. 170



Sleet & Freezing Rain (pp. 178-182)



- A warm layer above a cold surface can result in sleet or freezing rain. (Fig. 7.23, p. 182)
- Sleet (ice pellets) forms when rain freezes before reaching the ground. Requires deep freezing layer near ground.
- Freezing rain is rain that freezes after reaching the ground. Requires shallow freezing layer near ground.

Freezing rain: pretty but destructive (pp. 178, 180)

Fig. 7.21, p. 180

Freezing rain:

- Breaks trees and electrical cables (power lines, phone, cable TV) by the weight of the ice
- Makes roads very slippery and unsafe
- Ices aircraft (See "focus" section at top of p. 181.)

Most common in upper Midwest and New England (fig. 7.22, p. 181)

Hail (pp. 182-184)

- Hail forms when MANY cloud droplets freeze onto an “embryo” of almost any kind of particle (ice or even an insect).
- About 10 billion cloud droplets needed to form hailstone as big as a golf ball
- Cumulonimbus is only type of cloud with strong enough updrafts to support ice as big as hail for the 5-10 minutes it takes to grow.
- US has 500-700 hailstorms each year, causing hundreds of millions of dollars of damage.
- Record size hailstone in Aurora, NE on 8 June 2003 (p. 183), but lighter than 1970 hailstone at Coffeeville, KS. See http://www.usatoday.com/weather/news/2003-08-01-hailstone_x.htm
- Terminal velocity of Coffeeville hailstone estimated to be about 100 mph.

Measuring rain (pp. 184-185)

- Diameter of gauge unimportant
- Rain gauges contain funnels to magnify the effective rain depth (figs. 7.29 & 7.30)
- A tipping bucket rain gauge (fig. 7.30) has a pair of buckets that seesaw, alternately fill and dump rain every 0.01”
- “Trace of precip” is < 0.01 inches

Fig. 7.29, p. 184

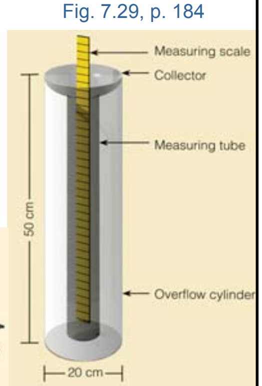


Fig. 7.30, p. 185

Measuring snow (p. 186)

- Because of drifting, snow depth is measured in 3 or more nearby places and averaged.
- Then a column of snow is melted to determine the liquid water equivalent.
- Typically, 10 cm of snow melts to 1 cm of water, i.e., 10:1 ratio of snow depth to liquid equivalent. So 10 inches of snow would melt to 1 inch of liquid.
- Very wet snow may be 6:1, and very light powder snow may be 30:1.
- Toward winter’s end, large compacted snow drifts may be 2:1.

Radar Estimates of Precipitation (pp. 186-187)

- Radar waves are scattered by rain or snow but not by cloud droplets (too small).
- Strength of radar echo is related to rain or snowfall rate, so radar can be used to estimate rainfall.
- On TV, they almost never show you the Doppler part of the display, only the echoes that can be seen with a traditional radar. In chapter 14, we’ll see how a Doppler radar is different from a non-Doppler radar.
- Satellites are also used to estimate rainfall, particularly in the tropics. High cold cloud tops are usually tops of thunderstorms. Calibrate by comparing cloud top temperature measured from infrared photo with rainfall measured at ground.