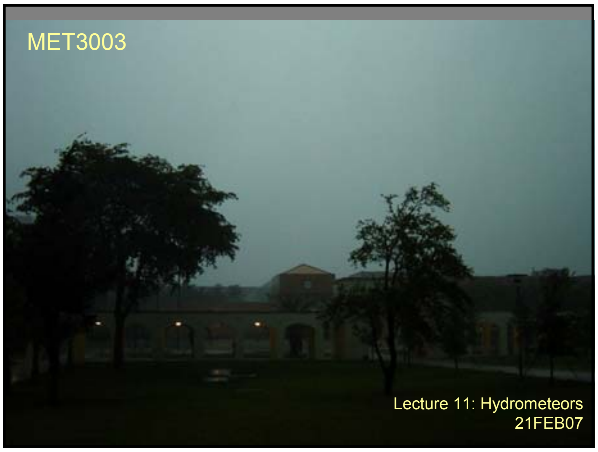


Atmospheric Aerosols

- Suspensions of solid or liquid in a gas, in this case air.
  - Clouds are aerosols, but in meteorology we usually mean different chemical composition than H_2O.
- **Sizes:** measured in μm (= 10^{-3} mm) to 0.01 μm. (human red blood cell ~ 5 μm).
- Because of friction and low mass aerospl particles fall 0.03 to 3 mm s^{-1} (i.e. a few meters a day)
- **Concentration:**
  - Oceans 10^3 cm^{-3}
  - Inland (clean) 10^4 cm^{-3}
  - Inland (polluted) 10^5 cm^{-3}
  - Primarily below 3-5 km altitude
- **Sources:** combustion, sea salt, some soils, decomposition of some plants
- **Sinks:** Coagulation, capture in clouds, fallout, precipitation scavenging

Some Definitions

- **Hydrometeor:** Any product of condensation, deposition, or freezing from the atmosphere whether in the atmosphere or on the Earth's surface. Also any water substance blown from the Earth's surface by wind---e.g. windblown spray or snow.
- **Precipitation:** Hydrometeors that fall <u>from a cloud</u> and reach the ground.
- Visible clouds are made of:
  - ***Cloud water***: Suspended droplets 10 μm in diameter (Middle Latitudes) or 15-60 μm in diameter (Tropics) that ***condensed*** directly from vapor
  - ***Cloud ice:*** Comparably sized crystals that ***deposited*** directly from vapor
  - Unfrozen liquid (***Supercooled***) water at temperatures below 0°C is common, particularly outside the tropics

Hydrometeors that are NOT Precipitation

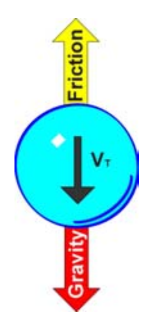
- ***Dew***: Liquid H_2O that condenses directly on the ground.
- ***Frost***: Ice that is deposited directly on the ground from vapor
- ***Rime***: Supercooled fog that freezes on contact with the surface
- ***Black Frost*** or ***Frozen Dew***: Condenses then freezes.

Kinds of Precipitation

- ***Rain***: Liquid water drops > 0.5 mm in diameter falling from the sky
- ***Drizzle***: Liquid water drops < 0.5 mm in diameter falling from the sky
- **Virga:** Like rain but evaporates before it reaches the ground.
  - Virga is a hydrometeor, but it <u>isn't precipitation</u>.
- ***Hail***: More or less spherical ice > 5 mm in diameter
- ***Graupel***: More or less spherical ice < 5 mm in diameter Note that the boundary between Hail and Graupel is 10x larger than the boundary between Rain and Drizzle
- **Snow**: Ice crystal deposited directly from vapor, or aggregates (clumps) of crystals
- Note that the boundary between Hail and Graupel is 10 times larger than the boundary between Rain and Drizzle

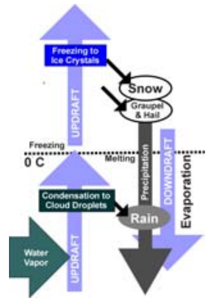
Terminal Velocity

- Hyrdometeors fall speed is a balance between friction and gravity.
  - Cloud particles: mm or cm s^{-1}
  - Rain up to 8 m s^{-1}
  - Snow 1-2 m s^{-1}
  - Hail > 10 m s^{-1}
- VT increases for
  - Lower air density
  - Hydrometeor size
  - Smoother hydrometeors



What Happens in a Cloud?

- Updraft leads to cooling and condensation.
- Forms cloud droplets, 10-50 µm in diameter.
- Cloud droplets collide and coalesce to form rain
- Are also carried upward to temperatures < 0ºC
- Many eventually freeze
- Ice grows faster than supercooled liquid H_2O
- Forms snow, graupel, and hail
- Which may melt to form rain if it falls below 0ºC level
- Precipitation loading and evaporative cooling force downdrafts.



Two Kinds of Precipitation

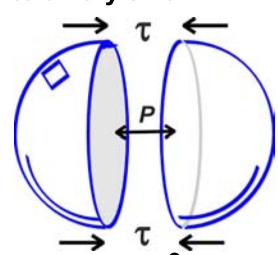
- Stratiform
  - Forced by large-scale flow
  - Updrafts a few cm s^{-1}
  - Falls from Nimbostratus
  - Drizzle, Rain & Snow
  - Cool season (sort-of)
- Convective
  - Buoyant updrafts
  - Updrafts several m s^{-1}
  - Falls from cumulonimbus
  - Rain, graupel & hail
  - Warm season

What are clouds made of?

- **Not of raindrops,** but of **suspended cloud droplets**---about 100 times smaller than raindrops, i.e. 10-80 µm (0.01-0.08 mm) in diameter.
- Let's start with cloud droplet formation in supersaturated air through **Condensation of water vapor**:
- **Homogeneous nucleation:** Water drops (or ice crystals) *might* form in pure air with nothing but dry air and H_2O involved.
- Each water molecule added has to do work against the surface tension.
- Thus, it is hard to make cloud droplets from scratch, because the amount of work per molecule is more when the droplet is smaller.
- Homogeneous nucleation requires **> 110% relative humidity** (or 10% supersaturation), which generally does not occur in the atmosphere.

It takes a lot of work against surface tension to add water to a very small drop

Very small droplets have so much surface area relative to their volumes and such high internal pressure that more H_2O atoms diffuse outward than inward.



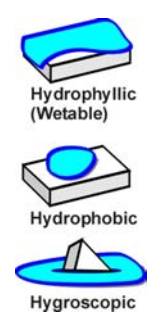
$$2\pi r\tau = \pi r^2 p, \quad \text{work} = pdV = \frac{2\tau}{r}dV$$

Heterogeneous nucleation

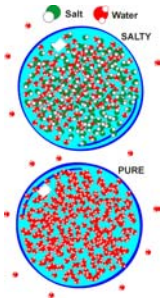
- Water drops (or ice crystals) form from the vapor on some sort of **substrate** or by **soaking** into a salt particle.
- For wetable nuclei, water attaches to the surface.
- For hygroscopic nuclei, water soaks into the surface and may actually dissolve the nucleaus.
- What makes a good ***Cloud Condensation Nucleus*** (CCN)?
  - Reasonably big (for an aerosol particle)
  - Easily wetable (0.1 µm) or soluble (0.01 **µm**).
- Over land, 100-1000 CCN cm^{-3} typically become active at 1% supersaturation
- Over the oceans, <100 CCN cm^{-3} typically become active at 1% supersaturation

Kinds of Condensation Nuclei

- For Hydrophyllic (wetable) nuclei, water attaches to the surface.
- For hydrophobic nuclei, water may bead on the surface,
  - But doesn't attach
  - Not good condensation nuclei
- For hygroscopic nuclei, water soaks into the surface and eventually dissolves the nucleus.



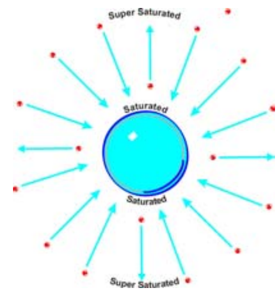
Solute effect:



- Dissolved "salt" blocks part of the surface, preventing H_2O molecules from escaping. Effective saturation vapor pressure is reduced.
- Proportional to: (number of H_2O molecules)/(number of H_2O + salt molecules) =
- Effect is weaker as the droplet grows, diluting the salt

Growth of Cloud Droplets by Diffusion

- The cloud becomes super-saturated
- Water vapor diffuses from high vapor density to low vapor density
- Rate of mass growth is proportional
  - Droplet area
  - Supersaturation
- Rate of growth of radius
  - Area is proportional to radius squared
  - Volume is proportional to radius cubed
  - Radius growth is inversely proportional to radius itself.
  - It's a bit trickier than the foregoing because the rate of diffusion also becomes smaller for larger droplets

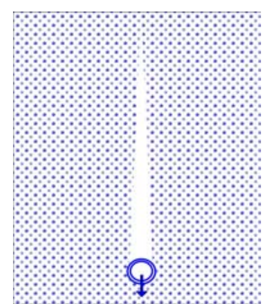


Limits to Growth by Diffusion

- The slowing of the growth rate means that there is a limit to the size drops can reach by diffusion.
- **NOTE: They can't form at all if they start out too small and they can't grow too big**
- **Continental clouds:**
  - 100-1000 CCN cm^{-3} ,
  - Small supersaturations,
  - All of the droplets are about 10 µm diameter
- **Maritime clouds:**
  - <100 CCN cm^{-3}
  - slightly larger supersaturations,
  - Wide range of droplet diameters, 20-50 µm.
- Both typically contain 1-2 gm m^{-3} of liquid water
- The biggest of these falls only about 30 cm s^{-1} , and cloud updrafts are often several m s^{-1}.
- So how do we get rain?

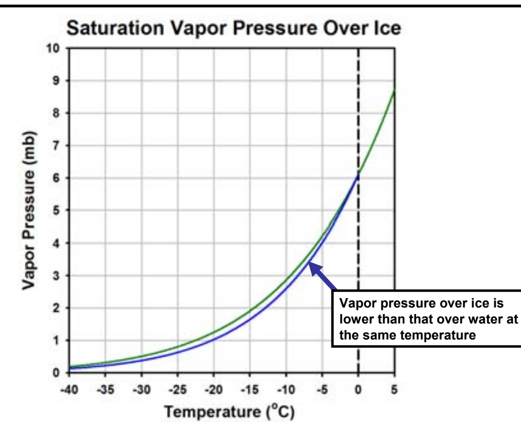
Growth of Warm Rain

- **Warm Rain:** Falls from clouds where T > 0°C throughout
- **Autoconversion:** A few droplets collide randomly and merge, becoming larger than the others
- Hydrometeors fall near their terminal velocity
- Larger, denser or rounder hydrometeors fall faster
- In clouds warmer than 0°C, precipitation forms when larger particles sweep up smaller ones as they fall through the cloud.
- Called ***Collision Coalescence***.



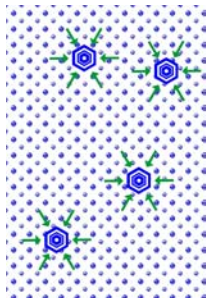
Collision-Coalescence

- Droplets bump into each other and merge to make bigger drops:
- Terminal velocity (6.5 m s^{-1} for a 1mm rain drop) of the larger drop allows it to overtake and capture cloud droplets.
- Some, or all, of the terminal velocities may be less than the updrafts velocity so that all of this can be moving upward, at least until the drops get big.
- **Coalescence efficiency** = fraction of drops or droplets in the cone that actually merge with collector drop.
- Varies from 0.2 for small droplets to > 1 for drops that are nearly the same size.
- Really big drops (> 2 mm) break up, and pieces are sometimes carried back up into the cloud for another go.
- Because of the broader initial droplet distribution, C-C works with a vengeance in tropical cumuli.



Mixed-Phase, Clouds, T<0°C

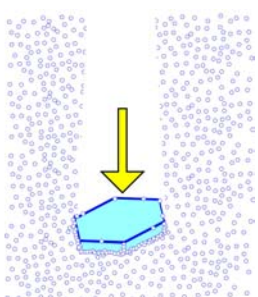
- Both freezing and condensation generally require nuclei to start the process
- Natural clouds have plenty of condensation nuclei (100,000/liter) but few freezing nuclei (10-100/liter)
- Consequently many clouds colder than 0°C contain ***Supercooled*** liquid $H_2$0 that has not yet frozen.
- May be as cold as -20°C
- When some ice does form,
  - the ice crystals grow
  - at the expense of supercooled water droplets
  - Bergeron-Findeisen process
- Artificial freezing nuclei can promote growth of snow that melts to form rain



Precipitation Growth Processes

- **Autoconversion:** When cloud droplets or ice crystals clump to form larger cloud droplets or drizzle
- **Collision-coalescence:** Rain drops grow by collecting cloud droplets or smaller rain drops
- **Riming:** Hail or graupel collect supercooled water that freezes on the collecting hydrometeor
- **Accretion:** Frozen hydrometeors collect cloud ice crystals or smaller frozen hydrometeors

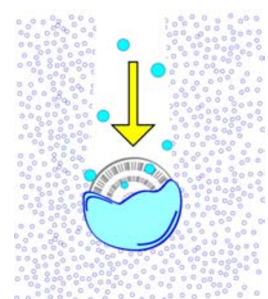
Riming



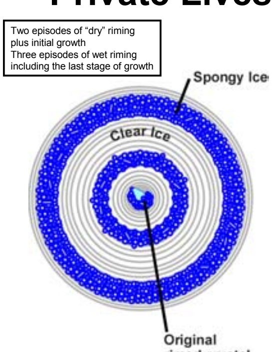
- Starts with a vapor-grown ice crystal
- Falling through a supercooled cloud
- Droplets freeze on leading edges.
- Forming spongy ice
- This is how graupel forms.

Wet Growth or Wet Riming

- Temperatures > -5°C
- Latent heat released by freezing keeps hailstone at 0°C.
- Coated with liquid water
  - Some freezes
  - Some is shed as drops at 0°C



Private Lives of Hailstones

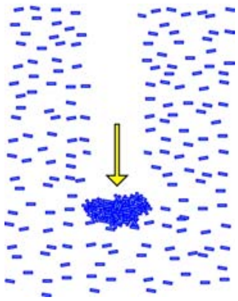


- Updrafts in Cb's are often stronger than hydrometeor terminal velocities.
- Leads to recycling of graupel and hail
- Forming multiple layers of clear and spongy ice
- In very strong updrafts hailstones can get really big---
- Coffeyville KS, 22JUN03
  - 18 cm diameter,
  - 750 gm

Hail Images

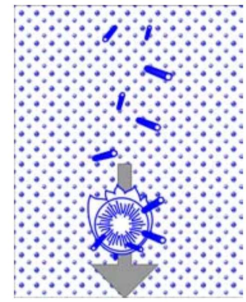
Aggregation

- Falling frozen hydrometeor collects other frozen hydrometeors
- Most snowflakes are aggregates of vapor-grown crystals
- Works best at temperatures > -5°C
- Big, soggy flakes vs. diamond dust



Ice Multiplication

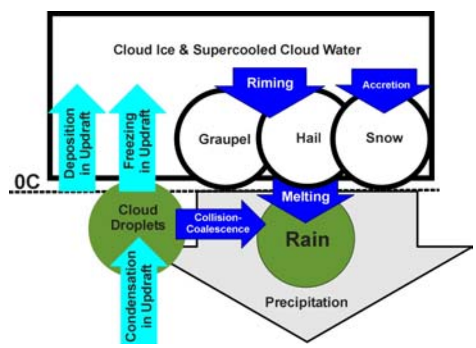
- Observatinos showed little ice in tropical Cb's
- Hallett-Mossup Process
  - Graupel falling in supercooled clouds grow whiskers-like ice crystals
  - Break off
  - Natural cloud seeding
- Happens in maritime clouds only
- Doesn't look good for cloud seeding in the tropics



Rain Gauges

(a) Simple rain gauge (b) Standard rain gauge (c) Tipping-bucket gauge

Precipitation Formation



Summary

- Know the definitions of ***Aerosol***, ***Precipitation*** and **Hydrometeors**
- Know the definitions of **Frost, Dew, Virga, Cloud Water (droplets) Cloud Ice (crystals)** and **Terminal Velocity.**
- Be able to explain ***Supercooled Water***, ***Homogeneous*** and ***Heterogeneous Nucleation.***
- Be able to explain how the different structure of maritime and continental cumuli arise from CCN concentrations in the parent air mass.
- Understand the growth of hydrometeors from vapor
- Be able to explain the ***Bergeron-Findeisen Process*** (ice crystal)
- Be able to expain the difference between ***Straitform*** and ***Convective*** precipitation.
- Be able to explain hydrometeror growth by ***Autoconversion, Collision-Coalescence, Accretion, and Riming***
- Be able to interpret the history of a hailstone from a cross section showing layers of clear and spongy ice
- Be able to explain how precipitation is measured with a rain gauge.
- **Reading for next time: *L&T* Chapter 6, Winds and Pressure**