Cloud Condensation Nuclei
- Dust
- Salt Particles from Sea Spray
- Natural Aerosols
- Human Created Pollution

Droplet Growth
- Condensation on Nuclei forms tiny embryos of liquid water
- Embryos will grow if $e$ is slightly more than $e_0$
- Growth is by diffusion of water molecules to the embryo (droplet)

Droplet Growth – Size vs. Mass

<table>
<thead>
<tr>
<th>Relative Size (diameter)</th>
<th>Relative Mass (depends on volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>64</td>
</tr>
</tbody>
</table>
Growth Times

(Growth Times from 1.0 um to Grown Size at RH=100.05 %
Labbook page 116)

<table>
<thead>
<tr>
<th>Droplet Diameter (um)</th>
<th>Growth Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>320 s</td>
</tr>
<tr>
<td>20</td>
<td>1800 s</td>
</tr>
<tr>
<td>100</td>
<td>1.20 hr</td>
</tr>
<tr>
<td>500</td>
<td>12.7 days</td>
</tr>
<tr>
<td>2000</td>
<td>201 days</td>
</tr>
</tbody>
</table>

Growth Times (cont.)

- Rate of Droplet Size Increase is Large at first
- Rate of Size Increase Quickly Decreases because of size – mass relationship
- Typical Cloud Droplet has a diameter of about 20 um.

The Question of Precipitation

- Types of Precipitation
  - Drizzle – drops less than 0.5 mm (500 um)
  - Rain – 500 – 6000 um (0.5 – 6 mm)
- Average Rain Drop has a diameter of about 2000 um (2 mm)
- How many cloud droplets (20 um) are necessary to make a rain drop (2000 um)

Answer

- 2000/20 = 100
- NO!
- Volume Proportional to (radius)³
  - (100³) = 10⁶
- It takes the liquid from 1,000,000 cloud droplets to make an average rain drop

Haze

- Some nuclei are very hygroscopic.
  - Condensation begins on these particles at relative humidities less than 75%.
  - Their size increases as the nuclei acquire more water.
  - At relative humidities less than 100%, the tiny droplets do not grow to cloud droplet size.
- The droplets are big enough to scatter all colors evenly but are too small to be seen by the naked eye.
- These droplets are seen as a whitish haze.

Haze

- Some particles are hygrophobic (water repelling).
  - They do not attract water molecules.
  - They remain small and tend to scatter blue light more so than red.
- The result is a bluish haze
  - Blue Ridge Mountains (“John-Boy Walton!”)
  - Smokey Mountains in NC and TN
Recipe for Clouds
- Plenty of water vapor
- A way to reach saturation and remain there
- Plenty of CCN
- Clouds will initially form as tiny droplets of water.
- What about if the air temperature is below 0°C ?????

Supercooled Water
- It is possible for liquid water to remain liquid below temperatures of 0°C.
- It is unlikely that molecules will go from a quasi-random state (liquid) to a rigid lattice (ice) without a little nudge.
- Liquid water below 0°C is called "supercooled" or "subcooled" water.
- All water will freeze below -40°C.
- The water molecules need a "gathering place" in which to group in an ordered fashion.

Precipitation formation through ice processes
- Ice forms on Ice Nuclei (IN)
  - Silicates
  - Clays
  - Combustion products
  - Industrial products

Nucleation of Ice
- IN activate as a function of temperature
- Contact nucleation
- Homogeneous nucleation
- Warm cloud tops (greater than -10°C) rarely have ice

Ice Crystal Growth
- Ice crystals grow by
  - Vapor deposition
  - Accretion of cloud droplets
  - Aggregation

Mixed Phase Clouds
Deposition of water vapor

Growth by Deposition

Ice Particle Multiplication
- Three processes
  - Fracture
  - Splintering during riming
  - Fragmentation of large drops during freezing

Growth in later stages

Ice Nuclei
- We had CCN for liquid water, so we need **Ice Nuclei** (IN) for the freezing process.
- Freezing Nuclei
  - These cause liquid drops to freeze

Ice Nuclei
- Deposition Nuclei
  - Water vapor deposits directly on the ice

The best ice nuclei are those that have shapes similar to natural ice crystals.

Kaolinite (a clay) is one of the most popular. It "activates," or begins to accept water molecules, at ~9°C.

Silver Iodide, which activates at ~4°C, has been used in "cloud seeding" experiments.

Typical cloud droplet size = 10 μm

This is about 100 times larger than a CCN and 100 times smaller than a typical rain drop.
The Precipitation Process

- How can a very small droplet grow to the size of a rain drop?
  - Typical Sizes (Radius)
    - CCN - 0.2 µm
    - Typical Cloud Droplet - 20 µm
    - Typical Rain Drop - 2000 µm (0.08"
  - How fast can this process occur?
  - In the tropics, a cloud can form, grow, and produce rain in as little as 30 minutes.

Droplet Growth by Condensation

- A droplet can grow only if the number of water molecules entering the drop exceeds the number of water molecules leaving the drop.
- Supersaturation!

Saturation Vapor Pressure

The saturation vapor pressure is defined over a plane (flat) surface of water.

- Each water molecule attracts its neighbor. The combined attractive forces on the molecules at the surface make up the surface tension.
- Consider the forces on the yellow molecule:
  - The forces on the yellow molecule are less than that for a plane surface of water. To maintain equilibrium, the vapor pressure above the drop must be greater in order to keep the drop from evaporating.

Curvature Effect

This reduced surface tension and the larger saturation vapor pressure required for the drop to remain in equilibrium with its surroundings is called the curvature effect.

This effect is enhanced for smaller drops. In other words, the smaller the drop radius, the larger the curvature of the drop, and the larger the vapor pressure required to keep the drop in equilibrium at a given temperature.
Curvature Effect

- Curvature Effect - Droplets with a smaller radius have a higher equilibrium vapor pressure.
- Air that is saturated w.r.t. a flat surface is unsaturated w.r.t. a curved surface.
- For droplets to exist, the surrounding air must be supersaturated (RH >100%)

Curvature Effect

- For droplets less than 1 mm, which is larger than for homogeneous nucleation, the supersaturations must be very high, well above what we see in the atmosphere, for the droplet to grow.

- This is a problem!!

- CCN to the rescue!

CCN to the Rescue!

- CCN give the water molecules a place to gather together. This “instantly” gives them a much larger size than without the CCN.

- Some CCN are hygroscopic. Some salts begin to collect water at RH’s as low as 75%. A solution is formed when water condenses onto a salt particle.

Solute Effect

- Solute effect - Equilibrium vapor pressure is less for a droplet with salt in solution.
  - Salt is hygroscopic and makes it harder for water to evaporate.

- Water droplets are competing among themselves for available water vapor.
  - Increasing RH results in larger droplets.

Solute Effect

The saturation vapor pressure is defined over a plane (flat) surface of water.

There are fewer water molecules at the surface. So not as many water molecules can escape at a given temperature. In equilibrium, the saturation vapor pressure over the salt water is less than that over the pure water. This is called the solute effect.
Solute Effect
The saturation vapor pressure is defined over a plane (flat) surface of water. Let us now consider a droplet.

![Diagram: Liquid H₂O → Add Salt → Salty H₂O]

The solution (salty) drop has a lower saturation vapor pressure than does the pure water drop. The solution drop can remain in equilibrium at relative humidities less than 100%.

This is opposite of the effect for curvature.

Köhler Curve
We can combine the effects of curvature and solution. This curve, represented by the thick line at the right, is the Köhler curve.

Initially the solution effect dominates, but as the drop gets bigger, the curvature effect takes over.

When the drop is very large, neither effect dominates and the surface of the drop, to the water molecules, appears as a flat surface.

Condensation
- Phase Change from Vapor to Liquid
- Release of Latent Heat of Vaporization
- Occurs When e = e_s
  - also RH = 100% or
  - mixing ratio = saturation mixing ratio
  - Temperature = Dew Point (T = T_d)

Example
- Parcel of air at the surface of the earth with a temperature T = 15°C and a dew point temperature of 3°C.
- How far will this parcel have to lift for condensation to occur?
- Looking for e = e_s or T = T_d

Lower T to T_d by Lifting
- T_p must decrease by
  \[ DT = T - T_d = 15 - 3 = 12°C \]
- Temperature of the parcel T decreases by 10°C for each kilometer of lift
- Amount of Lift Required is
  \[ L = (12°C)/(10°C/km) = 1.2 \text{ km} \]
- Cloud Base should form 1.2 km above the surface of the earth
Condensation

- $e = e_s$ is valid for flat surface of water
- In clean air RH of 800% is required to have water condense and form droplets
- If ions are present RH of about 400% is required to form droplets in clean air
- Condensation at RH = 100% requires a surface to get process started

Condensation Nuclei

- **Particles** that provide a surface area upon which water molecules can get organized into the liquid phase when $e = e_s$
- Almost any type of particle will work, in the atmosphere dust, smoke, sea salt
- Generally there is a sufficient number of these particles in the atmosphere so condensation occurs when $e = e_s$

Hygroscopic Nuclei

- Some particles such as Sea Salt have an affinity for water molecules
- These particles can initiate condensation when $e$ is slightly less than $e_s$
- Condensation (clouds) may be somewhat easier to form if hygroscopic nuclei are present (oceans, coastal zones)

Growth by Condensation

- **Given:**
  - CCN with an initial mass of $10^{-12}$ g
  - RH greater than RH’ (The critical RH)
  - How long will it take for a droplet to grow to the size of a cloud droplet ($20 \text{ mm}$)?
  - 5900 sec
  - ~98 Minutes!
  - This is too slow for what we often observe!

Cloud Droplet Growth by Condensation (Diffusion)

- Driven by the saturation vapor pressure difference
- Vapor is transported from higher to lower saturation vapor pressure
Vapor Growth

Vapor Transport

Vapor transport between drops

Evolution of cloud drop size

Collision and Coalescence

- Consists of two steps
- Will the droplets collide?
- If so, will they coalesce?

Terminal Velocity

In the absence of any wind, the drop will begin to fall.

As soon as the drop falls, the air resists the fall of the drop.

The air resistance is dependent on the size of the drop and the velocity of the drop. So the larger the drop will have a larger air resistance.
Terminal Velocity

Eventually, there will be a balance between gravity, which wants to pull the drop down toward the ground, and the air resistance, which wants to retard the fall of the drop to the ground.

From Newton, when there is a balance of forces, the drop will continue in a straight line at constant speed. This speed is called the **Terminal Velocity**.

The larger drops will have a larger terminal velocity than small drops so the large drops will fall faster.

In calm air, a typical rain drop will fall nearly 600 times faster than a typical cloud droplet.

Collision and Coalescence

- Collisions begin at radius of 18 microns
- Collision efficiency increases as the size of the colliding drop increases

Collision and Coalescence

- Not all collisions result in coalescence
- Coalescence is affected by turbulence, surface contaminants, electric fields and charges
- Broad droplet spectra favor more collisions

Efficient cloud characteristics

Narrow droplet spectrum

Heterogeneous droplet distribution
Droplet Breakup and Multiplication
- Falling drops sweep out a cone-shaped volume
- Drops are unstable just after coalescence
- Droplet breakup broadens the spectra and limits the maximum size

Collision-Coalescence Process
- To increase the volume of a single drop to the size of a rain drop, it must grow for a very long time.
- A faster way is to get several small drops together to form a single large drop.
- Larger drops fall faster than small drops.

Collision-Coalescence Process
- If the larger drops fall faster, they can catch up to and run into the smaller drops.
- If the large drops collide with the smaller drops and merge with them, this process is called coalescence.
- Not all small drops will merge with the larger ones!

Collision-Coalescence Process
- Coalescence Depends On:
  - Cloud Water Content
  - Large Droplet Size
  - Small Droplet Size
  - Updrafts (Relative speed of the large drop to the small drop.)
  - Cloud Electricity
  - A drop will grow quickly by this process.

Rain Drops Keep Falling On My Head
- The drops can make it to the ground if:
  - The drop is large enough
  - The cloud base is low enough
  - The air between the cloud base and the ground is not too dry.
Are Rain Drops Tear Shaped?

From this picture, it seems that something is pulling at the top of the drop.

Is this realistic?

Consider a small drop that is not falling.

The forces on each molecule are inward. The total force wants to pull the molecule toward the center of the drop. This results in a spherical droplet.

Are Rain Drops Tear Shaped?

As the drops fall, the air resistance force is applied at the bottom of the drop.

The air resistance force pushes on the bottom of the drop. As the drop falls faster, the air resistance force increases. Surface tension will try to keep the drop a sphere. The combination of the two gives the resulting drop a "hamburger bun" shape.

Are Rain Drops Tear Shaped?

No drops fall in the shape of a tear drop. They usually have a flat bottom and a slightly oval shape.

If the drop is large enough, the air resistance forces can actually "inflate" the drop. The drop then breaks up into many smaller drops. This is called "bag breakup."

This sets an upper limit on the size of raindrops.

The Question of Precipitation

- What % of all Clouds Produce Precipitation?
- What is the minimum amount of time necessary produce precipitation?
- How is Precipitation Produced (limitations)?
- Why does a warm stratus cloud produce smaller rain droplets than a warm cumulus cloud?
- Why does a layer of snow make it quieter?
- If both ice crystals and water droplets are present in a cloud, which will grow faster?
- What is the purpose of cloud seeding?
- How to use cloud seeding concept to suppress the formation of hail?

Fill the blanks

- Cloud droplets are _____ X _____er than typical rain drops.
- Droplets size will __________ if they are at their equilibrium vapor pressure.
- Snow scatters light ___________ than rain; therefore, the bottom of rain clouds are _______er than snow clouds.
- Most precipitation begins as ____________ .
- Pieces of ice ranging from the size of small peas and larger are called _____________ .
- Light shower of snow is called ___________.
- Intense shower of snow is called ___________

- A heavy snow will reduce visibility to _____ km.
- Low temperatures and >30 knot winds which bear large amounts of small snow particles is called ________ .
- Tiny ice pellets, bounces when it hits the ground are called _____________ .
- A melted snowflake or raindrop freezes when it hits a cold surface layer of air and forms _____________.
- If the cold surface layer is shallow, the raindrops will not freeze before hitting the ground giving ______________.
< 1/100 in. of rain is called a ________.
For fresh snow the equivalent amount of rain is _____/____ as much.
Water droplets at temperatures below freezing are __________.
A cloud is ___________ (only ice particles) at temperatures below -40°C.
Growth of large droplets as they overtake smaller droplets and merge with them is called ______________.
Saturation vapor pressure over ice is __________ than that over water.