Atmospheric Physics

Lecture 17

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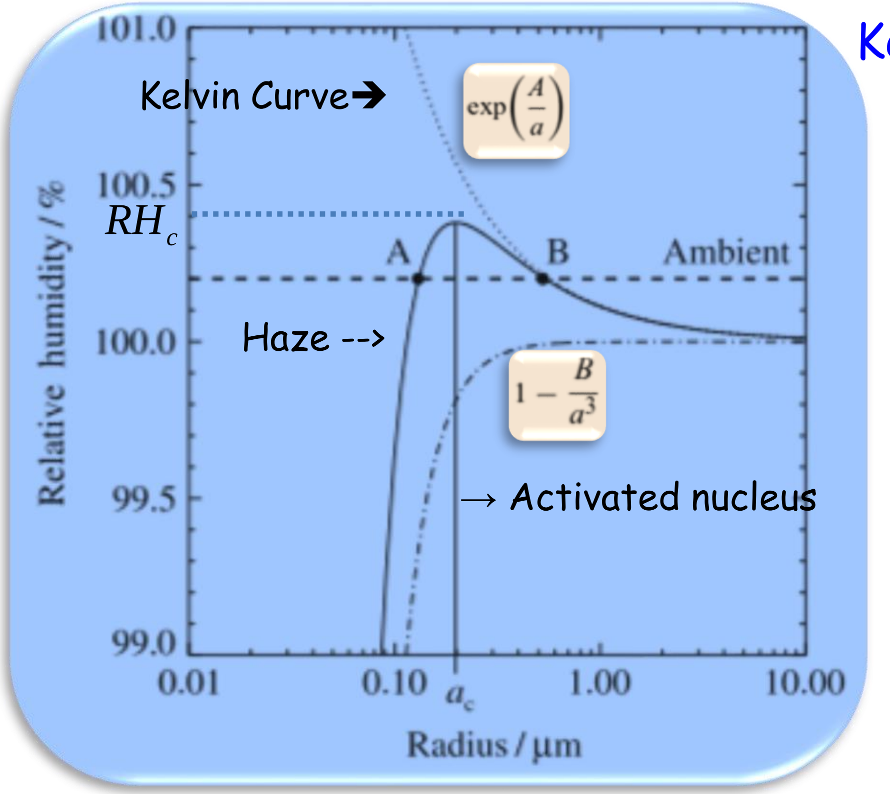
Fig. gives an example of this function of radius a

Köhler curve

$$RH \equiv \frac{e}{e_s(T)} = \exp\left(\frac{A}{a}\right)\left(1 - \frac{B}{a^3}\right)$$

Equilibrium (Saturation) Curve
e Near Drop = e of Environment
(particle doesn't change size)



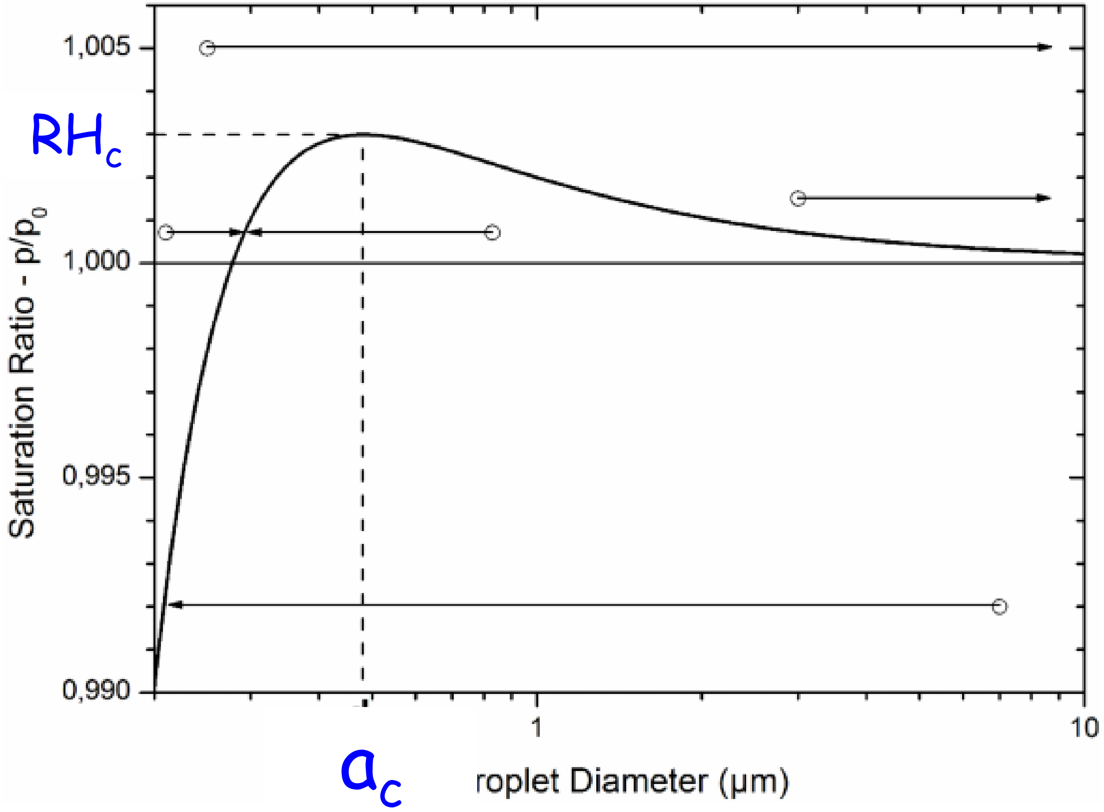
Kelvin factor exp(A/a)

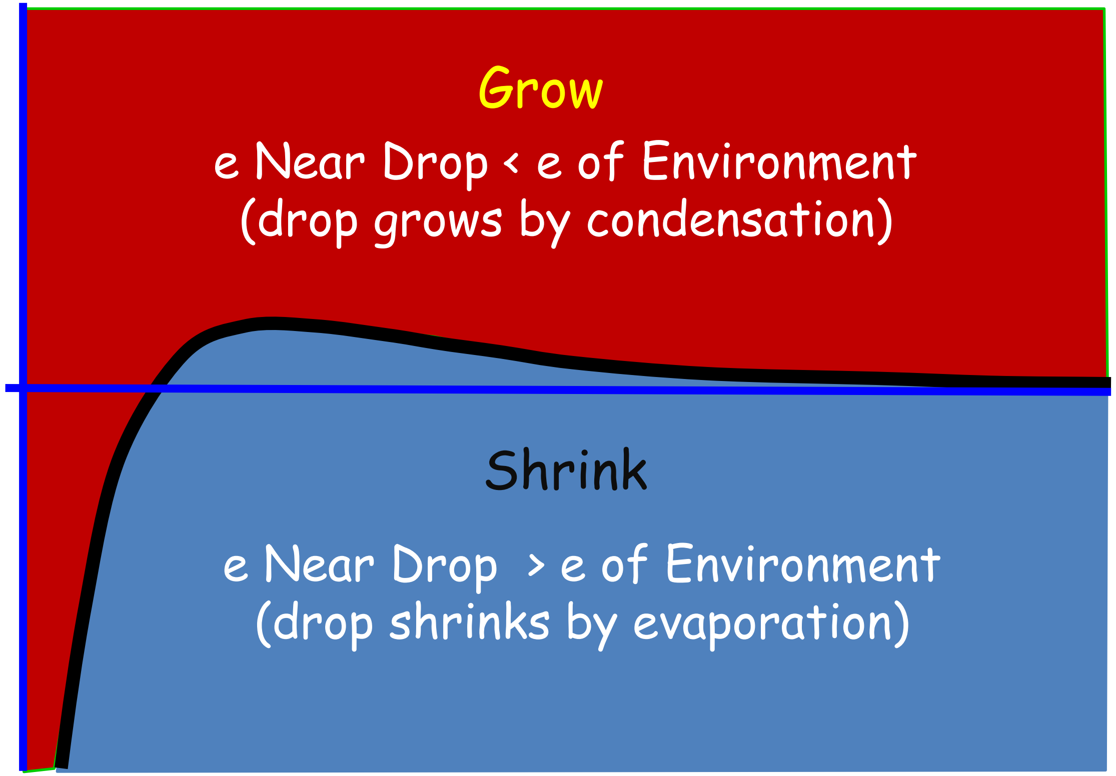
which decreases with increasing a,

Raoult factor

which increases with increasing a

Figure shows the Köhler equation applied to an NaCl particle that has the diameter 0.05 μm when completely dry.




Grow
e Near Drop < e of Environment
(drop grows by condensation)
Shrink
e Near Drop > e of Environment
(drop shrinks by evaporation)

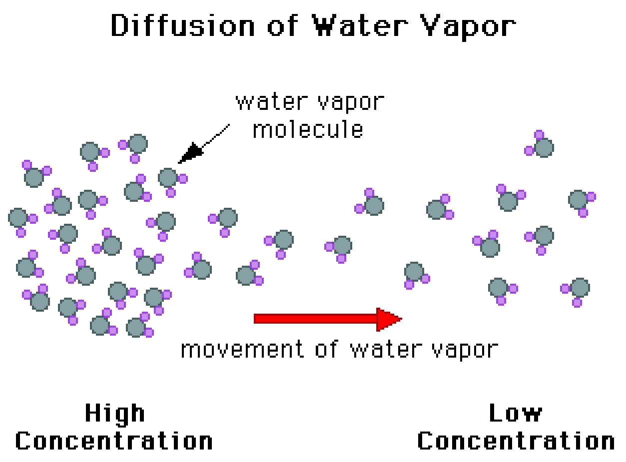
Droplet growth by diffusion

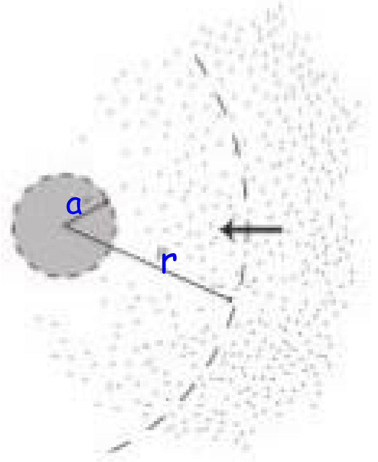
The rate of growth of the droplet depends on two things

1) The gradient in vapor concentration from the surface of the droplet to the ambient environment the presence of supersaturation, i. e., a relative humidity H greater than the equilibrium relative humidity H of the droplet.

Diffusional growth gives narrow size distribution.

2) The surface area $4\pi r^2$





The analysis given above considers only the water vapour in the immediate neighbourhood of the droplet.

Fick's law of diffusion

However, if the droplet is to grow, there must be a continual supply of water vapour to its surface.

This can happen by diffusion if there is a vapour density gradient in the region surrounding the droplet, with the vapour density increasing with distance.

A simple representation of this diffusion is in terms of Fick's law

$$f = -D\nabla\rho_v = -D\frac{d\rho_v}{dr}$$

ρ_v vapour density,

f vapour-flux vector - has units of mass/(unit area·unit time)

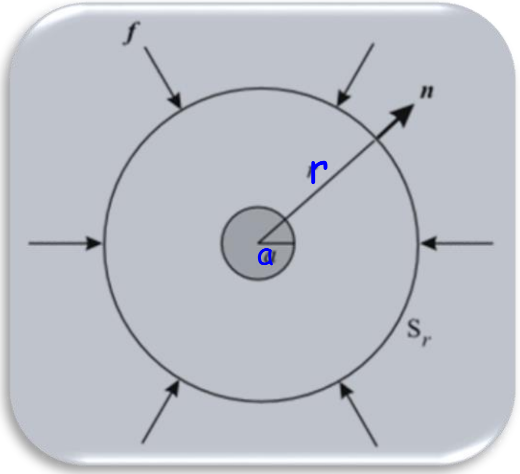
D diffusion coefficient of water vapor in air, assume constant

Assuming that at some instant the radius of the droplet is a and that the distribution of the vapour density is spherically symmetric,

$$\rho_v = \rho_v(r),$$

the total inward flux of mass of vapour through a sphere S_r of radius $r > a$ is

$$-\int \vec{f}.\hat{n}ds = \int D\nabla\rho_v ds = D\frac{d\rho_v}{dr}\int ds = D\frac{d\rho_v}{dr}4\pi r^2$$



Where n is the outward normal to S_r

However, water vapour is lost only by condensation at $r = a$,

so for

$$r > a$$

this flux must be independent of r and equal to the rate of increase of mass of the droplet,

$$dM_l / dt$$

$$D \frac{d\rho_v}{dr} 4\pi r^2 = \frac{dM_l}{dt} \qquad \frac{d\rho_v}{dr} = \frac{dM_l / dt}{4\pi D} \frac{1}{r^2}$$

Which can be integrated from $r = a$ to $r = \infty$ to give

$$\rho_v(a) = \rho_v(\infty) - \frac{1}{4\pi Da} \frac{dM_l}{dt}$$

using the ideal gas law for the vapour,

$$\rho_v = e/(R_v T)$$

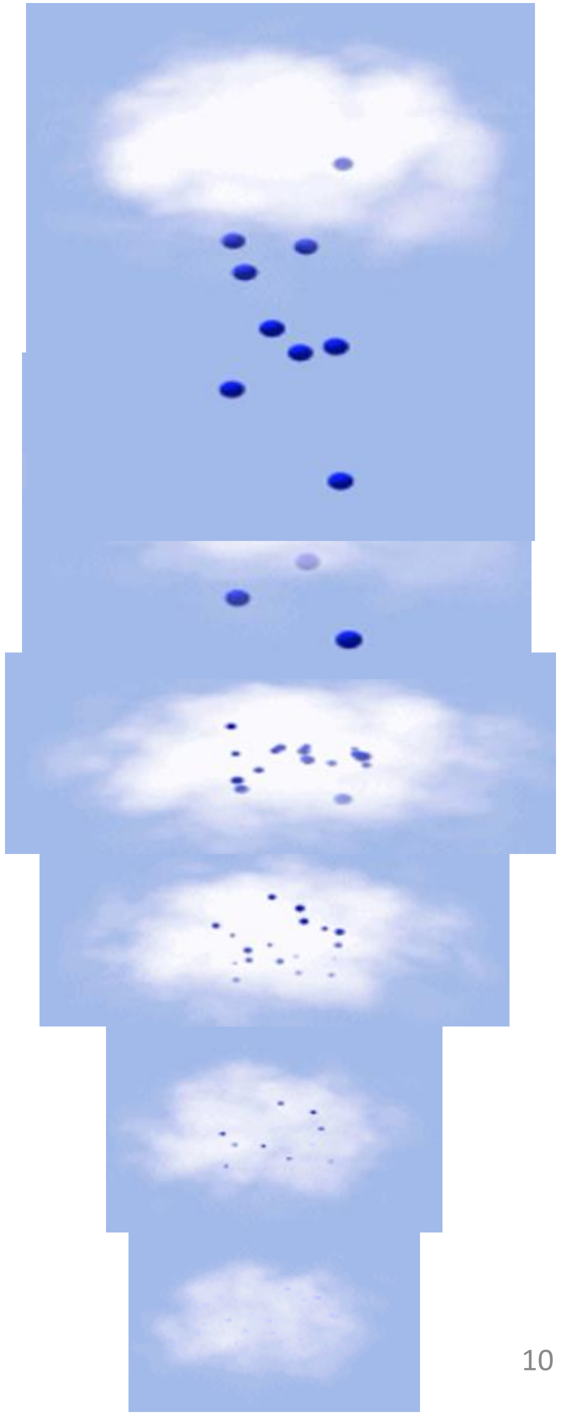
$$\frac{dM_l}{dt} = 4\pi Da\left[\rho_v(\infty) - \rho_v(a)\right] = \frac{4\pi Da}{R_v}\left[\frac{e(\infty)}{T(\infty)} - \frac{e(a)}{T(a)}\right]$$

$e(\infty)$ vapour pressure

$T(\infty)$ temperature far from the droplet

$e(a)$ and $T(a)$ at its surface

Droplet growth by collision and coalescence



When collisions occur, drops either bounce apart or coalesce into one larger drop.

Cloud droplets will be carried by air currents within the cloud, and if they bump into each other, it is called a collision.

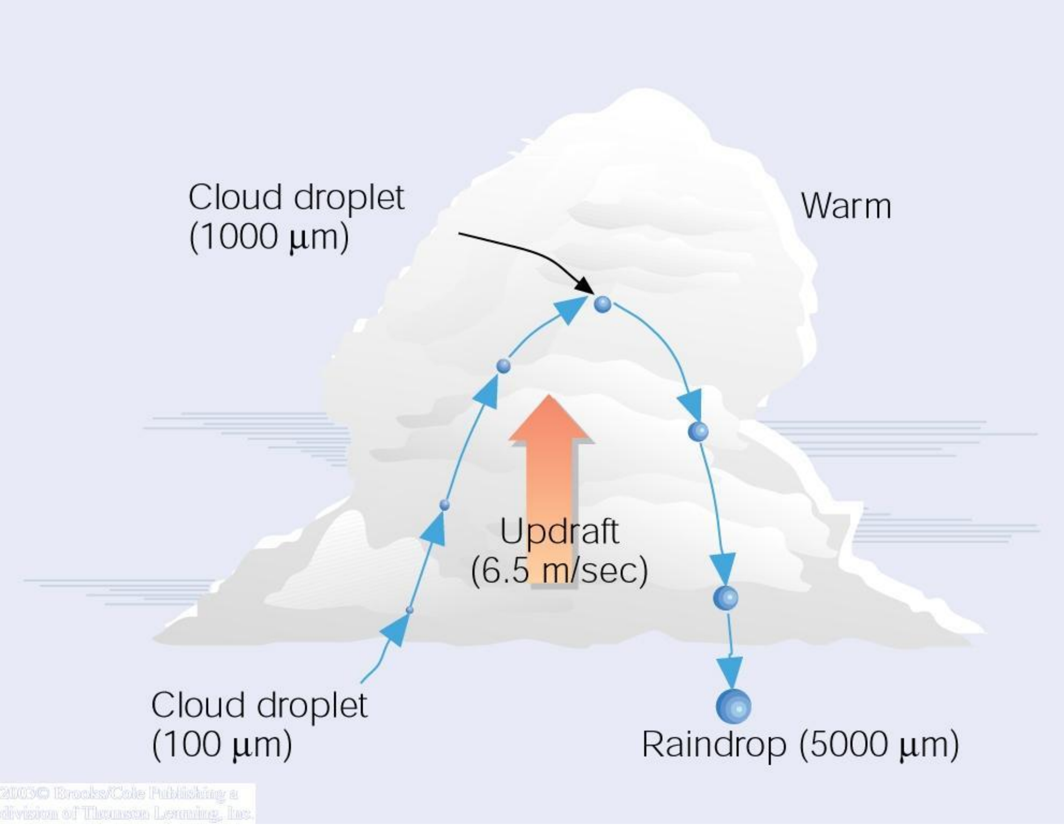
However, if they collide then stick together, that is called coalescence.

Although this process is important, especially in the tropics, it falls short of being the primary mechanism for the formation of raindrops.

Updrafts in a cloud can transport a droplet upward repeatedly allowing it many opportunities to fall back down through the cloud and collide and coalesce with other droplets..

Collision-Coalescense Process

Collision and coalescence operates in warm clouds (> 15 ^{0}C) to produce rain, and is affected by the clouds liquid water content, droplet sizes, cloud thickness, updrafts, and drop electrical charges.



Collision

Collector drops collide with smaller drops.

Collisions typically occur between a collector and fairly large cloud drops.

Smaller drops are pushed aside.

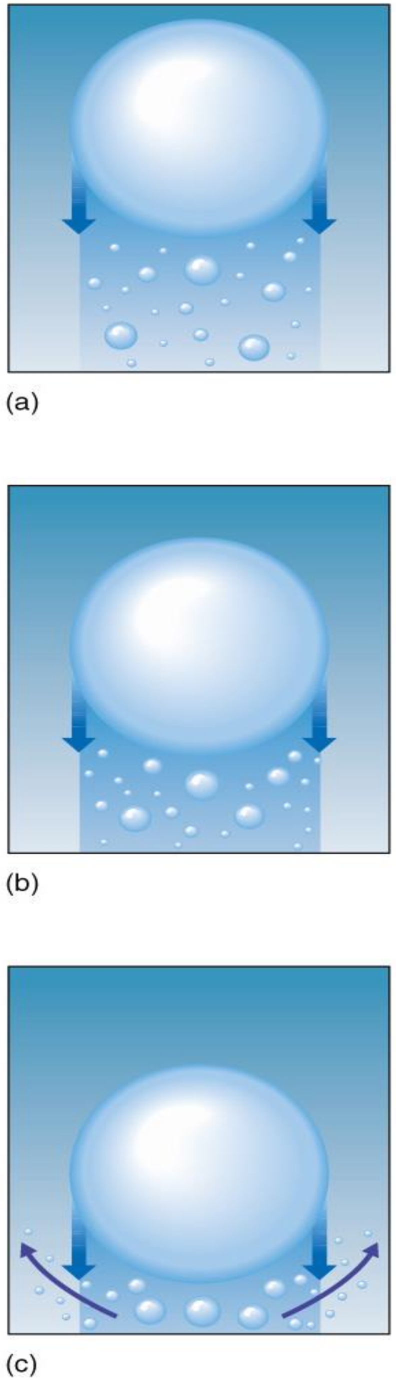
Collision is more effective for the droplets that are not very much smaller than the collect droplet.

Most clouds formed in the Tropics, and many in the middle latitudes, are warm clouds (greater than 0°C).

The Collision-coalescence process generates precipitation.

This process depends on the differing fall speeds of different-sized droplets.

It begins with large collector drops which have high terminal velocities.



Rain Drops Keep Falling On My Head

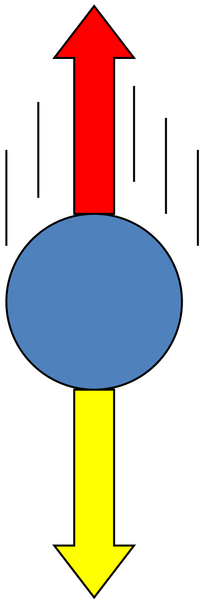
The drops can make it to the ground if:

The drop is large enough

The cloud base is low enough

The air between the cloud base and the ground is not too dry.

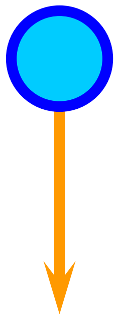
Terminal Velocity



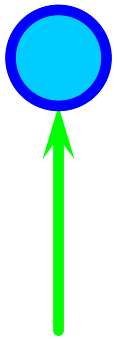
$$\frac{1}{2} C \rho_{air} A \upsilon^2 = mg$$

$$\upsilon = \sqrt{\frac{2mg}{C \rho_{air} A}}$$

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.

Typical sizes (diameter)

Condensation nuclei: 0.2 µm

Cloud droplet: 20 µm

Raindrop: 2000 µm

The cloud droplets need to grow in order to become raindrops!

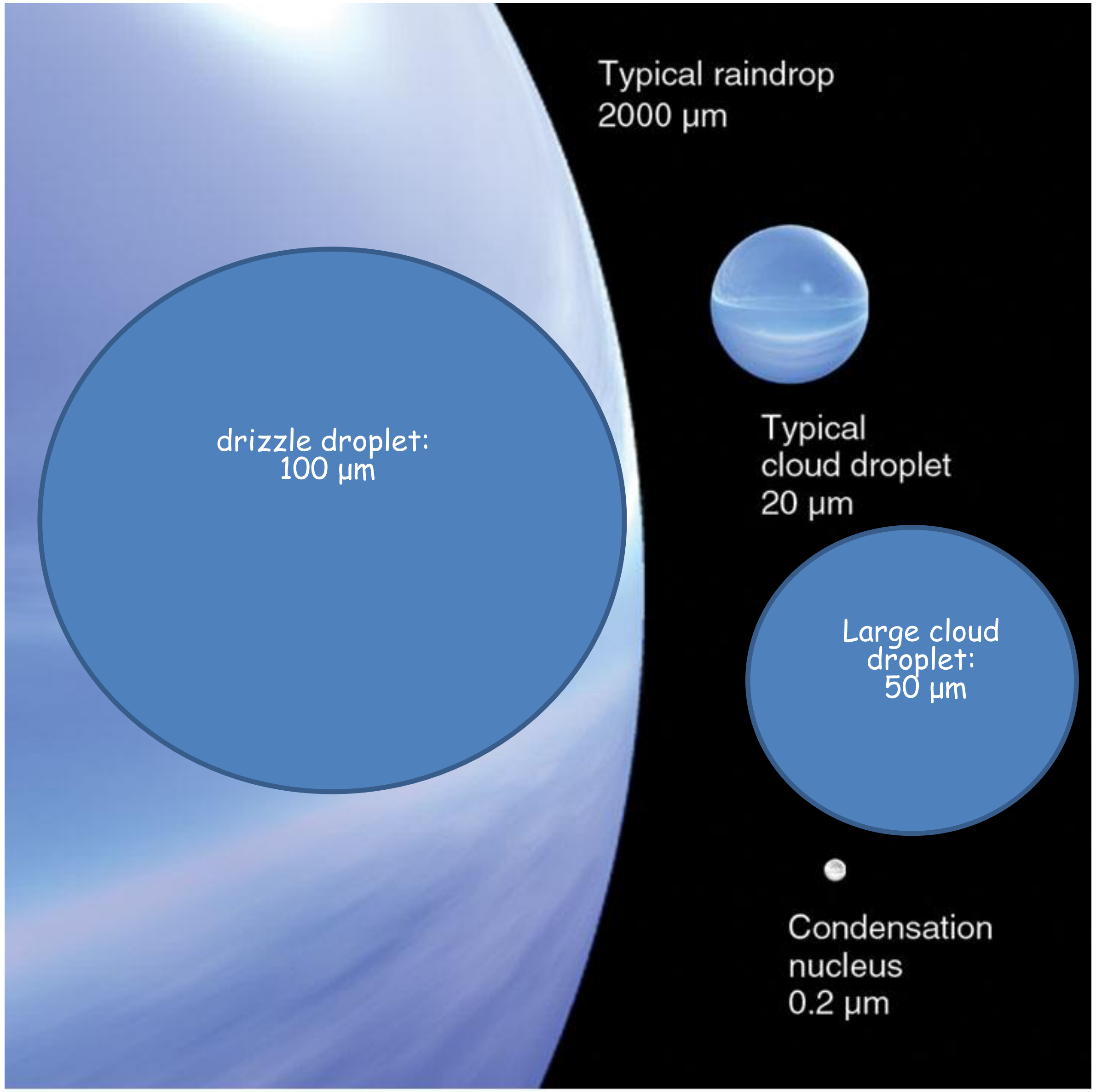
Growth is determined by the balance of condensation (C) and evaporation (E)

C>E the droplet grows

C<E the droplet gets smaller

C=E the droplet stays the same (in equilibrium), hence:

Saturation (equilibrium) vapor pressure



Terminal Velocity of Different-Size Particles Involved in Condensation and Precipitation Processes

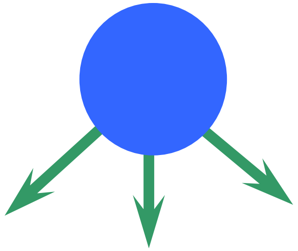
TERMINAL VELOCITY			
Diameter (μm)	m/sec	ft/sec	Type of Particle
0.2	0.0000001	0.0000003	Condensation nuclei
20	0.01	0.03	Typical cloud droplet
100	0.27	0.9	Large cloud droplet
200	0.70	2.3	Large cloud droplet or drizzle
1000	4.0	13.1	Small raindrop
2000	6.5	21.4	Typical raindrop
5000	9.0	29.5	Large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

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.



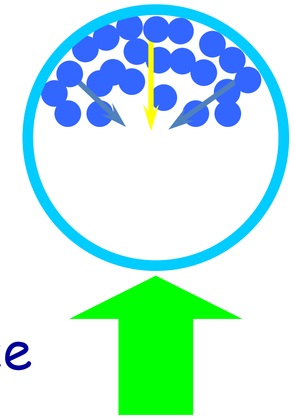
The forces on each molecule are inward.

The total force wants to pull the molecule toward the center of the drop.

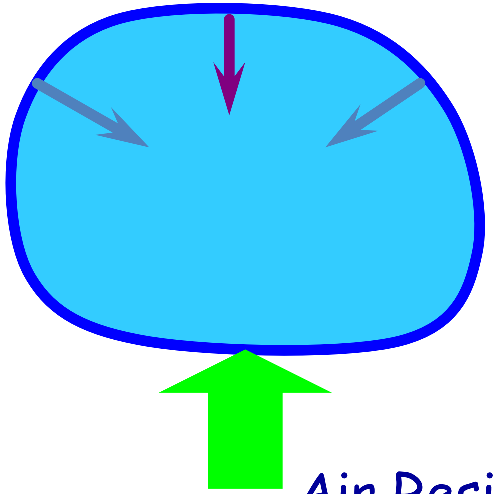
This results in a spherical droplet.

Are Rain Drops Tear Shaped?

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



Air Resistance



Air Resistance

The air resistance force pushes on the bottom of the drop.

As the drop falls faster, the air resistance force increases.

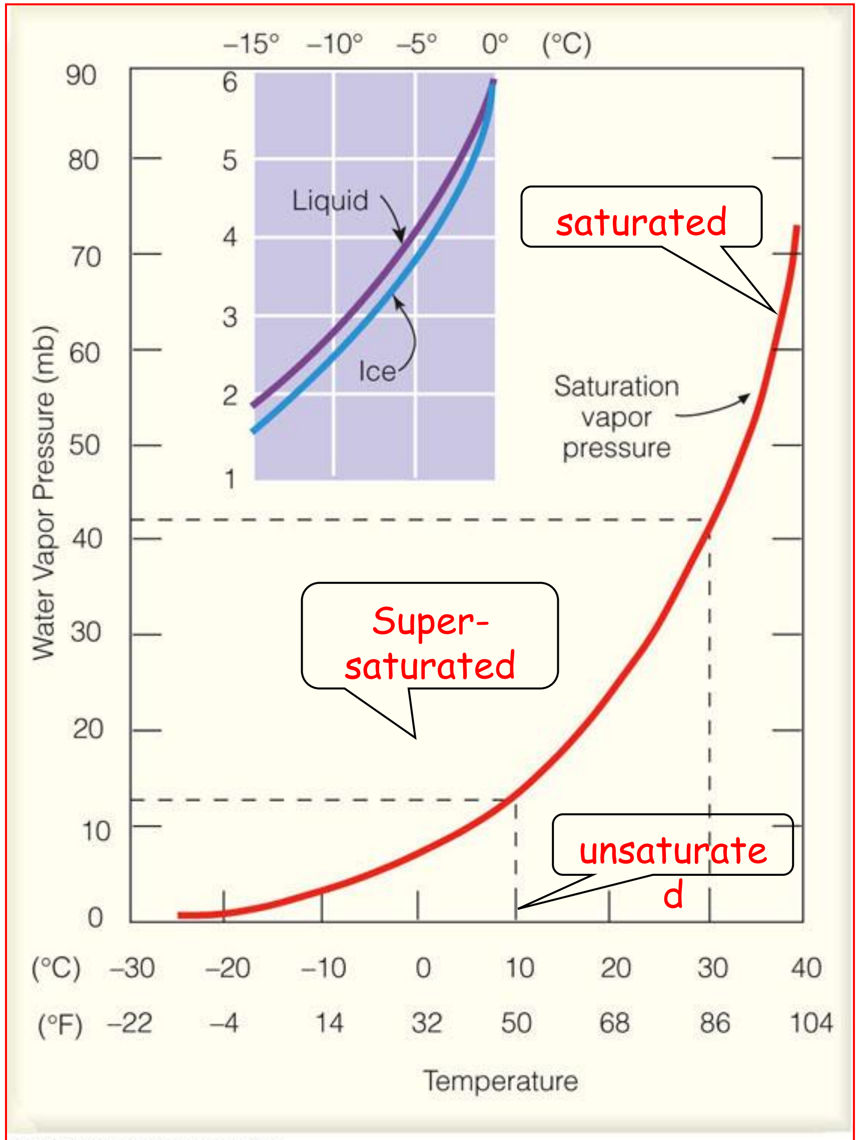
Surface tension will try to keep the drop a sphere.

The combination of the two gives the resulting drop a “hamburger bun” shape.

Saturation Vapor Pressure

The saturation vapor pressure e_s, depends on the temperature. It increases with temperature.

e_s over water is larger than it is over an ice surface at the same temperature.



"Cold" clouds

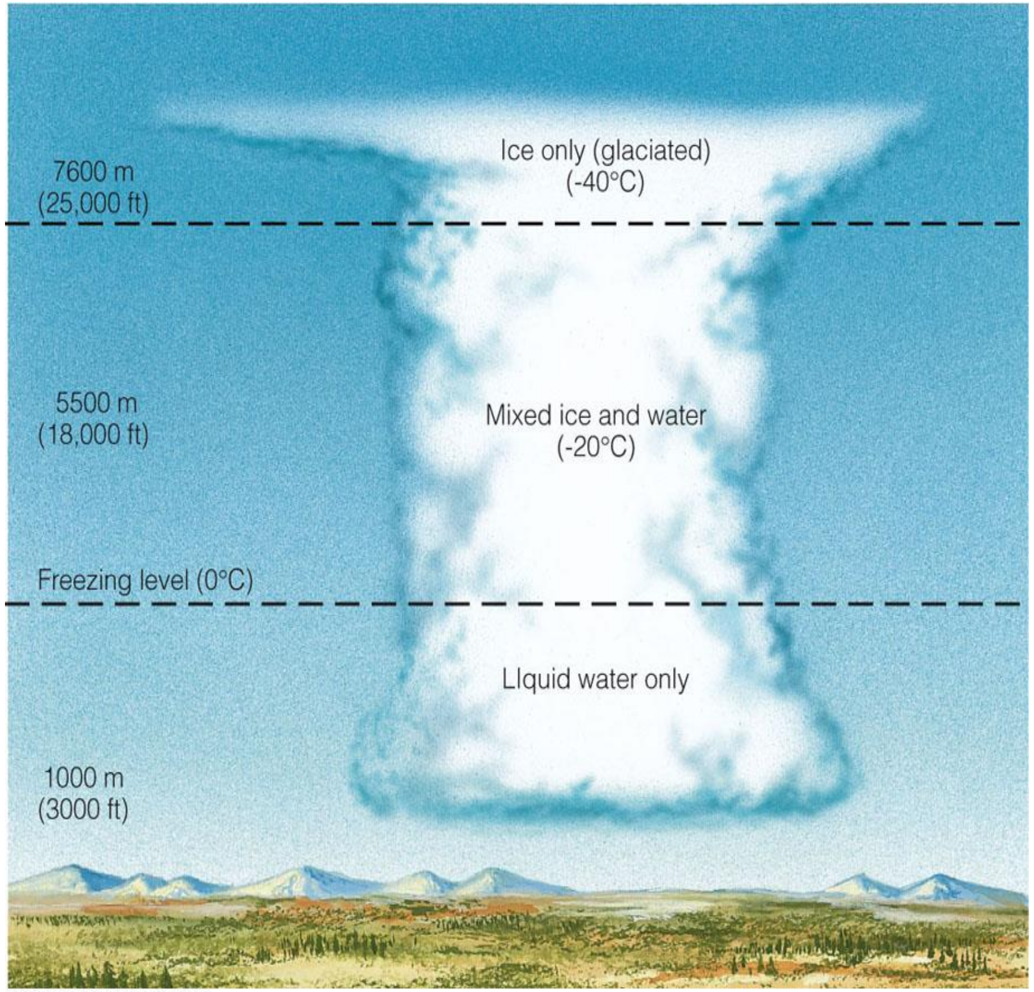
The temperature of a "cold" cloud drops below the water freezing point.

Below 0 ^{0}C the cloud water droplets are supercooled.

The smaller the droplet, the lower the temperature at which it will freeze.

Below -40 ^{0}C almost all droplets freeze and form ice crystals.

Small particles in the air serve as ice nuclei: freezing nuclei



HOW PRECIPITATION FORMS

There are two processes in which meteorologists and scientists say precipitation forms:

1) Collision and Coalescence Process
2) Ice-Crystal Process

ICE CRYSTAL PROCESS

The next precipitation process is the following four categories:

(1) Equilibrium

(2) Deposition

(3) Graupel

(4) Bergeron Process

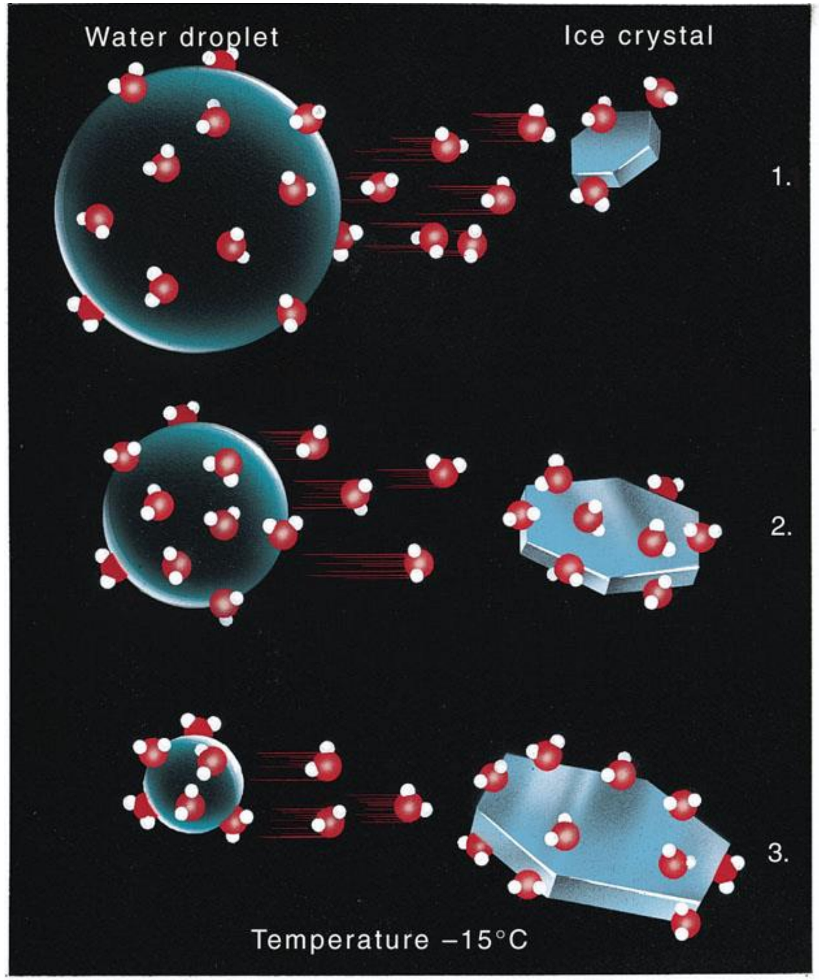
Ice-crystal (Bergeron) process

The saturation vapor pressure above a water surface is larger than the saturation vapor pressure above an ice surface.

Water molecules evaporate more easily than ice molecules

Water vapor molecules migrate towards the ice crystals.

Cloud ice crystals grow at the expense of the water droplets.



Ice-crystal Process

called the Bergeron process

extremely important in mid and high latitudes

air below freezing

cloud are called cold clouds

Example: next slide

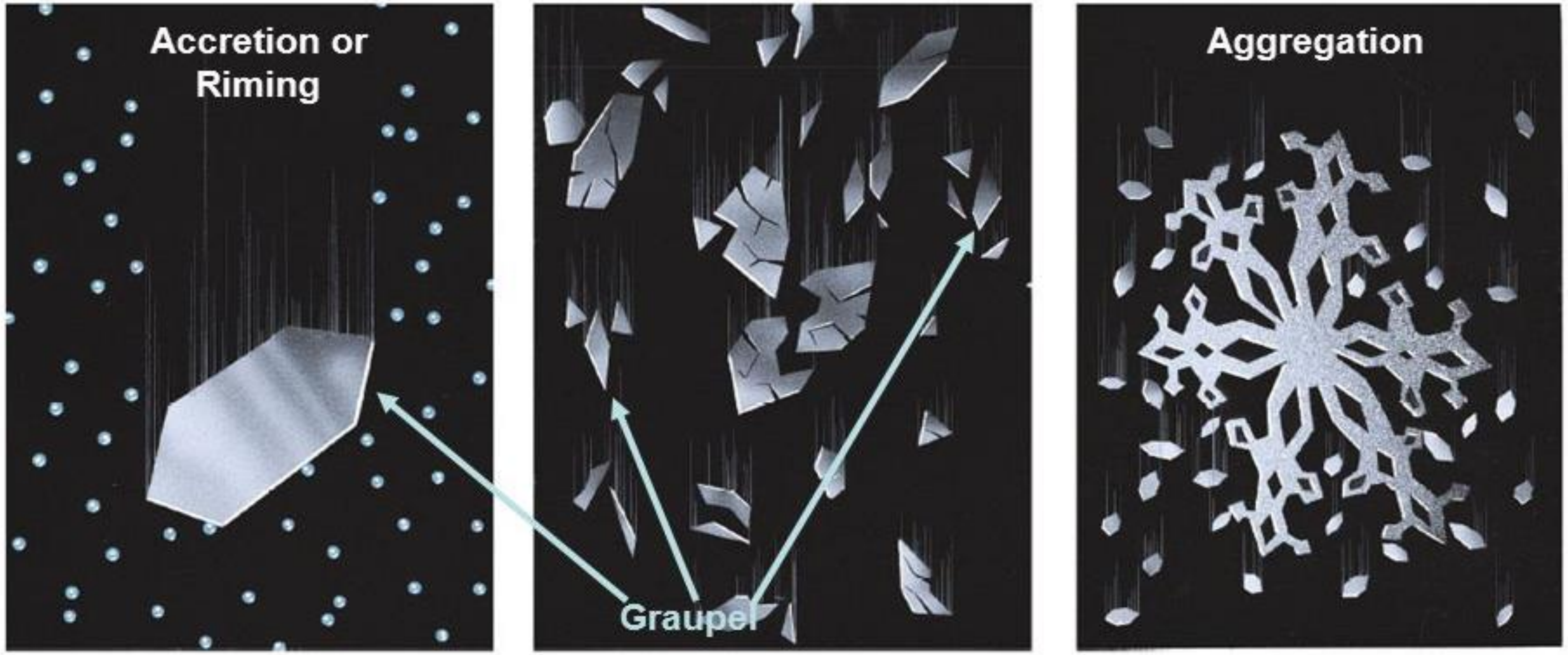
ice crystals form on ice nuclei

number of ice nuclei available in the atmosphere is small

deposition nuclei - allows water vapor to deposit as ice directly onto their surfaces

freezing nuclei - promote the freezing of supercooled liquid water

contact nuclei - cause freezing after being immersed in liquid



(a) Falling ice crystals may freeze supercooled droplets on contact (accretion), producing larger ice particles.

(b) Falling ice particles may collide and fracture into many tiny (secondary) ice particles.

(c) Falling ice crystals may collide and stick to other ice crystals (aggregation), producing snowflakes.

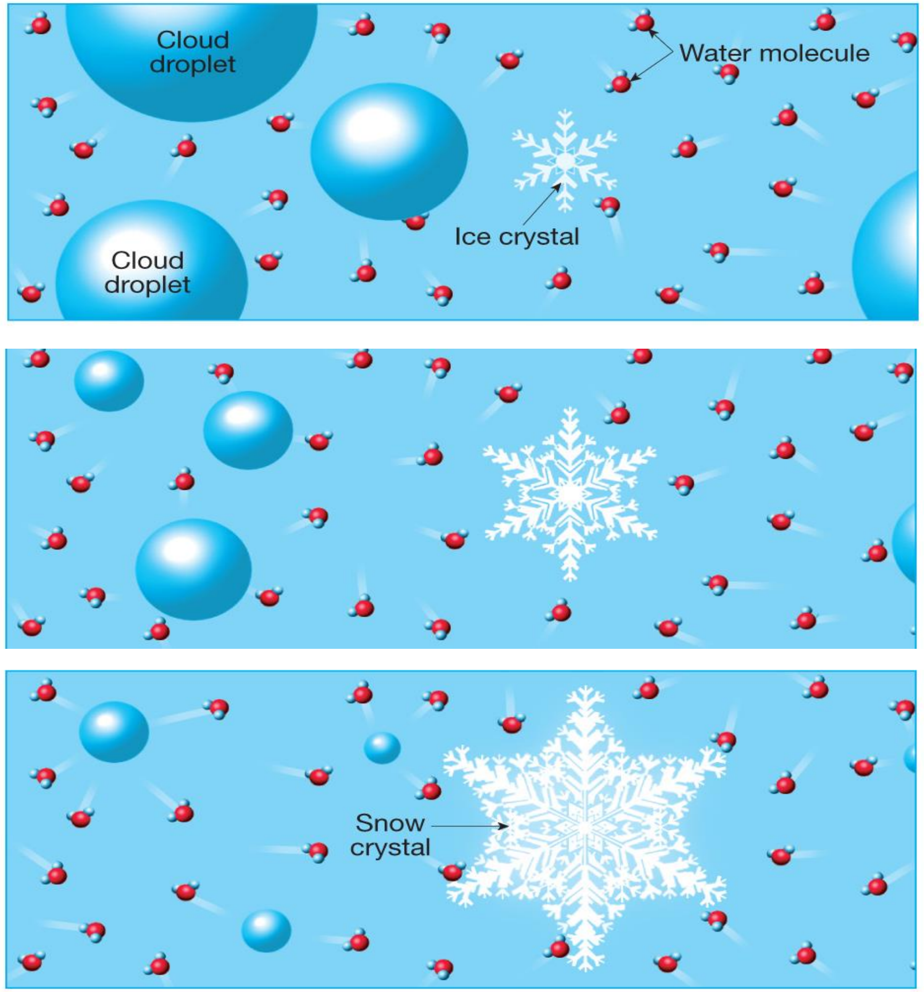
•As ice crystals fall and collide with super cooled drops, they get bigger by accretion.

•Falling icy matter is called graupel (snow pellet), and aggregation describes the joining of two ice crystals into snowflakes.

•If the snowflake melts while falling, it continues down as a raindrop.

•Much of the rain, even in the summer, in the middle and northern latitude falls as snow initially.

The Bergeron process



Precipitation

Forms of precipitation

Rain and drizzle

Rain – droplets have at least a 0.5 mm diameter

Drizzle – droplets have less than a 0.5 mm diameter

Snow – ice crystals, or aggregates of ice crystals

Sleet and glaze

Sleet

Wintertime phenomenon

Small particles of ice

Precipitation

Forms of precipitation

- Sleet and glaze
  - Sleet
    - Occurs when
      - Warmer air overlies colder air
      - Rain freezes as it falls
  - Glaze, or freezing rain – impact with a solid causes freezing

Precipitation

Forms of precipitation

Hail

- Hard rounded pellets
  - Concentric shells
  - Most diameters range from 1 to 5 cm

Formation

- Occurs in large cumulonimbus clouds with violent up- and downdrafts
- Layers of freezing rain are caught in up- and downdrafts in the cloud
- Pellets fall to the ground when they become too heavy

Precipitation

Forms of precipitation

- Rime
  - Forms on cold surfaces
  - Freezing of
    - Supercooled fog, or
    - Cloud droplets