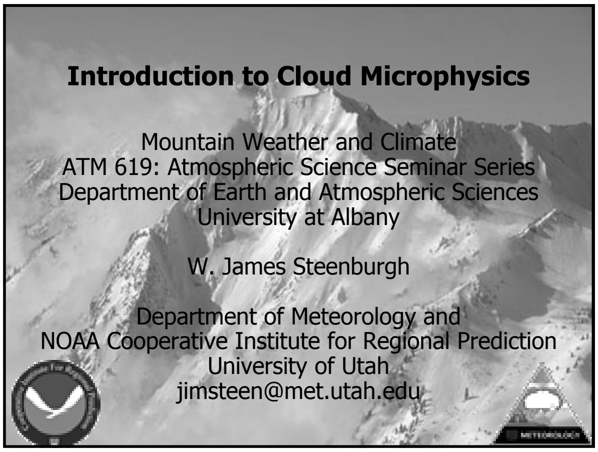

Introduction to Cloud Microphysics

Mountain Weather and Climate
ATM 619: Atmospheric Science Seminar Series
Department of Earth and Atmospheric Sciences
University at Albany

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Dalton's law of partial pressures

- The total pressure exerted by a mixture of gases equals the sum of the partial pressure of the gases

$$p = p_{0_2} + p_{N_2} + e$$
$$e = p_{H_2 0} \ (vapor\_pressure)$$

- *Partial pressure* – pressure a gas would exert if it alone occupied the volume the entire mixture occupies
- Meteorologists differentiate between "dry" gas partial pressure and water vapor partial pressure (vapor pressure)

$$p = p_d + e$$

Mixing ratio

- Measure of the amount of water vapor in the air
- Ratio of mass of water vapor to the mass of dry air in a volume of air

$$w \equiv m_v / m_d$$

- Units g/kg (use g/g or kg/kg in calculations)
- Typical values
  - Midlatitude winter = 1-5 g/kg
  - Midlatitude summer = 5-15 g/kg
  - Tropics = 15-20 g/kg
- Conserved following parcel motion if there is no net condensation/evaporation

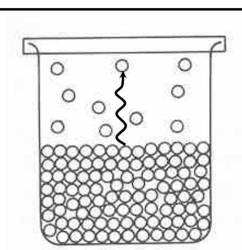
Mixing ratio/vapor pressure relationship

- Relationship between mixing ratio and vapor pressure

$$e = \frac{w}{w + .622} p$$

- Assuming mean sea-level pressure (1013 mb)
  - Midlatitude winter = 1-5 g/kg ~ 1.5-8 mb
  - Midlatitude summer = 5-15 g/kg ~ 8-24 mb
  - Tropics = 15-20 g/kg ~ 24-32 mb
- Thus, e<<p

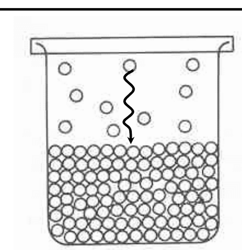
Evaporation



Bohren (1987)

- Water molecules moving from liquid to vapor phase
- Accompanied by latent cooling
- *Always* occurring

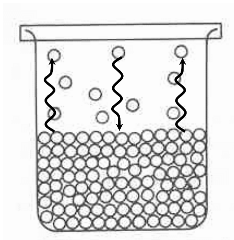
Condensation



Bohren (1987)

- Water molecules moving from vapor to liquid phase
- Accompanied by latent heating
- *Always* occurring

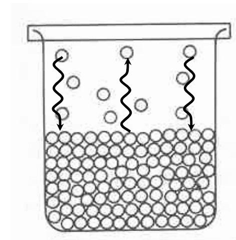
Net evaporation



Bohren (1987)

- What we commonly refer to as evaporation is when the rate of evaporation exceeds the rate of condensation

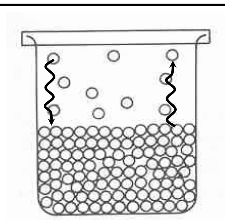
Net condensation



Bohren (1987)

- What we commonly refer to as condensation is when the rate of condensation exceeds the rate of evaporation

Equilibrium and saturation vapor pressure



Bohren (1987)

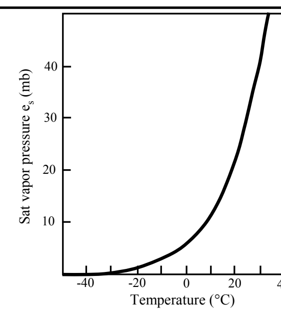
- *Equilibrium vapor pressure* – evaporation and condensation are occurring, but are in equilibrium
- *Saturation vapor pressure* – equilibrium vapor pressure for a plane surface of pure water
- For solutions and cloud droplets, equilibrium vapor pressure does not necessarily equal the saturation vapor pressure

Saturation vapor pressure

- Varies with temperature

$$e_s \cong 6.11 \exp[\frac{L}{R_v}(\frac{1}{273} - \frac{1}{T})]$$

- L=latent heat of condensation
- R_v = gas constant for water vapor (461.5 J/kg/K)



Wallace and Hobbs (1977)

Saturation mixing ratio

- The ratio of the mass (m_{vs}) of water vapor in a given volume of air that is saturated with respect to a plane surface of pure water to the mass (m_d) of dry air

$$w_s = \frac{m_{vs}}{m_d}$$

- Relationship to saturation vapor pressure

$$w_s = .622(\frac{e_s}{p - e_s}) \cong .622 \frac{e_s}{p}$$

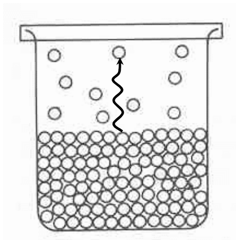
Relative humidity, dewpoint, and supersaturation

- *Relative humidity* (with respect to water) - the ratio (%) of the actual mixing ratio to the saturation mixing ratio at the same temperature and pressure

$$RH \equiv 100 \frac{w}{w_s}$$

- *Dewpoint* - the temperature to which air must be cooled at constant pressure for it to become saturated with respect to a plane surface of pure water
- *Supersaturation* = RH-100

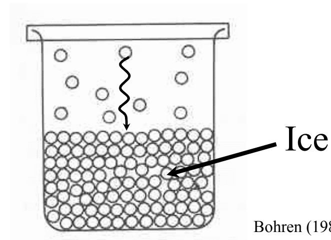
Evaporation of ice (sublimation)



Bohren (1987)

- *Sublimation* occurs when water molecules move directly from ice to vapor phase (no liquid phase)
- Accompanied by latent cooling
- *Always* occurring

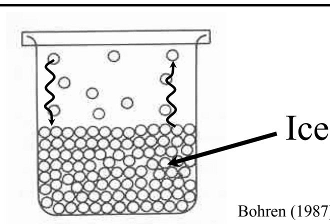
Vapor deposition



Bohren (1987)

- Water molecules move directly from vapor to ice phase
- Accompanied by latent heating
- *Always* occurring
- Also called deposition or vapor deposition

Equilibrium and saturation vapor pressure for ice

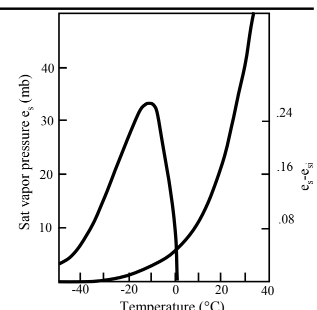


Bohren (1987)

- *Equilibrium vapor pressure for ice* – sublimation and deposition are occurring, but are in equilibrium
- *Saturation vapor pressure for ice* – Equilibrium vapor pressure for a plane surface of pure ice
- For solutions and ice particles, equilibrium vapor pressure for ice does not necessarily equal the saturation vapor pressure for ice

Saturation vapor pressure for ice

- The saturation vapor pressure for ice is ≤ that for water
  - $e_{si}=e_s$ at 0°C
  - Otherwise $e_{si}<e_s$
  - e_s-e_{si} is largest at –10°C to –15°C



Wallace and Hobbs (1977)

Saturation mixing ratio with respect to ice

- The ratio of the mass (m_{vs}) of water vapor in a given volume of air that is saturated with respect to a plane surface of pure ice to the mass (m_d) of dry air

$$w_{si} = \frac{m_{vsi}}{m_d}$$

- Always less than or equal to the saturation mixing ratio with respect to water
  - $w_{si}=w_s$ at 0°C
  - $w_{si} \leq w_s$ if T<0°C

Relative humidity with respect to ice

- *Relative humidity* (with respect to ice) - the ratio (%) of the actual mixing ratio to the ice saturation mixing ratio at the same temperature and pressure
  - RH wrt ice > RH wtr water (equal at 0°C)

$$RH \equiv 100 \frac{w}{w_{si}}$$

- *Frost point* - the temperature to which air must be cooled at constant pressure for it to become saturated with respect to a plane surface of pure ice
  - Frost point > dewpoint (equal at 0°C

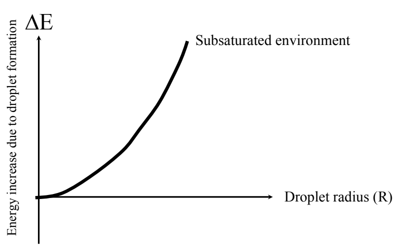
Formation of cloud droplets

- Clouds can form when the air becomes supersaturated with respect to water (or ice)
- Usually occurs due to adiabatic cooling produced by ascent
- Can also occur due to
  - Radiational cooling (e.g., radiation fogs)
  - Sensible cooling (e.g., advection fogs)
  - Mixing (e.g., contrails)
  - Other processes that cool or moisten parcels
- The formation of a cloud droplet is called *nucleation*

Homogeneous nucleation

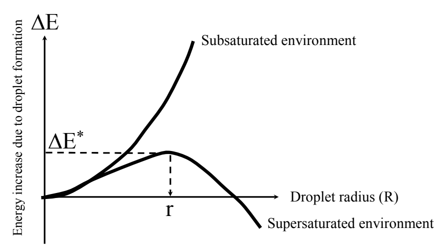
- *Homogeneous nucleation*: Formation of a *pure* water droplet by condensation without the aid of a particle suspended in the air
- Growth of a cloud droplet represents a battle between
  - Work required to create more droplet surface area (called the interfacial energy or surface energy)
    - Proportional to the R^2, where R is the droplet radius
  - Energy provided to the system by condensation (Gibbs free energy)
    - Proportional to R^3
- This battle means that the saturation vapor pressure is a function of droplet radius (known as the *Kelvin effect*)

Homogeneous nucleation



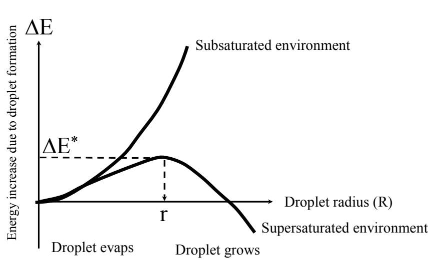
- In subsaturated air, the energy needed to increase droplet surface area is too big for energy released by condensation to overcome
- Droplets form through molecular collisions, but quickly evaporate

Homogeneous nucleation



- In supersaturated air, the energy required to increase the surface area ($\propto R^2$) exceeds that released by condensation ($\propto R^3$) for small droplets
- Beyond a critical radius, r, the energy released by condensation exceeds that needed to increase surface area and droplets spontaneously grow

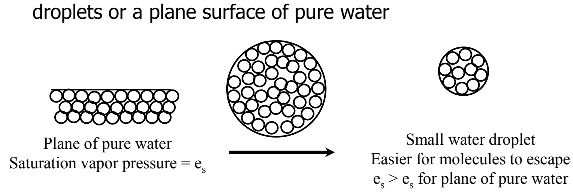
Homogeneous nucleation



- The critical radius is where
  - The droplet is at its equilibrium vapor pressure (evaporation = condensation)
  - It could either evaporate or grow if it shifts one way or the other

Homogeneous nucleation

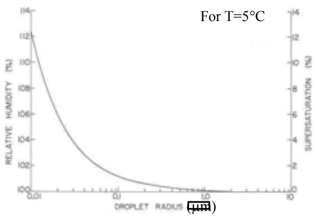
- Why? It's easier for water molecules to "escape" if the radius is small (more surface area/molecule)
- Evaporation rate for small droplets is greater than for large droplets or a plane surface of pure water



- Equilibrium vapor pressure is larger for small droplets
- Need large supersaturation for a pure cloud droplet to grow

Homogeneous nucleation

- For a given temperature, equilibrium vapor pressure (and RH) increases with decreasing droplet radius
- If r=.01 μm, equilibrium RH is 112.5% (for T=5C)
- RH>103% is rarely observed
- It's very difficult for homogeneous nucleation to occur (except when opening beer cans)



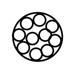
Heterogeneous nucleation

- How do clouds form?
  - They get help: Heterogeneous nucleation
- *Heterogeneous nucleation*: Formation of a cloud droplet on an atmospheric aerosol
- Atmospheric aerosols that are soluble in water dissolve when water begins to condense on them
- The solution lowers the equilibrium vapor pressure & creates more favorable conditions for droplet growth

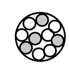
Heterogeneous nucleation

- In a solution, there are fewer water molecules on the water surface available for evaporation
- Evaporation rate is lower than for pure water
- Equil. saturation vapor pressure is *lower* than for pure water

Heterogeneous nucleation

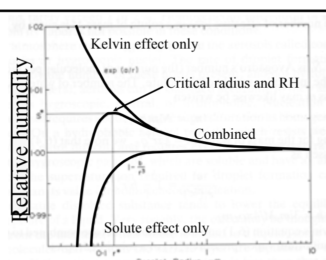


Small pure water droplet
Surface is all water molecules
Largest possible evaporation rate
Maximum equilibrium vapor pressure



Small solution droplet
Surface has fewer water molecules
Less evaporation
Smaller equilibrium vapor pressure

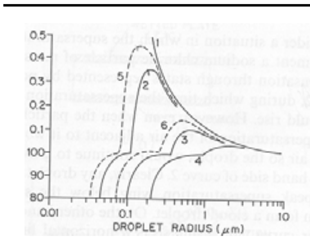
Heterogeneous nucleation



Rogers and Yau (1989)
Kohler curve for droplet
Formed on 10^{-16} g
ammonium sulfate particle

- Kohler curve: Combines solute and Kelvin effects
- Equilibrium RH lowered for small droplets by solute effect
- Kelvin effect does result in a critical RH for nucleation of > 100% (in this case 100.6%)

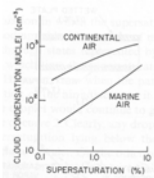
Heterogeneous nucleation



Wallace and Hobbs (1977)

- Kohler curves, critical RH, and critical radius vary with type and concentration of solution
- A droplet that has passed over its Kohler curve peak is called *activated*
- Not all droplets are activated – there are winners and losers!

Cloud condensation nuclei



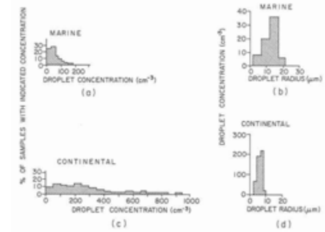
Wallace and Hobbs (1977)

- *Cloud condensation nuclei (CCN)* – Aerosol which serve as nuclei for water vapor condensation
- The larger and more soluble the aerosol, the lower the supersaturation needed for activation
- There is an order of magnitude more CCN in continental air than maritime air

Cloud condensation nuclei

Maritime

Continental



Wallace and Hobbs (1977)

- Continental clouds feature
  - Large cloud droplet number concentrations
  - Smaller cloud droplets
- Maritime clouds feature
  - Smaller cloud droplet number concentrations
  - Larger cloud droplets

Microphysics of cold clouds

- *Cold cloud* – a cloud that extends above the 0°C level
- Water does not necessarily freeze at 0°C
  - Analogous to the formation of a cloud droplet, a water droplet will only freeze if it results in a decrease in the total energy of the system
- *Supercooled cloud droplets* – Cloud drops that exist at temperatures below 0°C
- *Mixed cloud* – A cloud consisting of both ice particles and supercooled cloud droplets
- *Glaciated cloud* – A cloud consisting entirely of ice

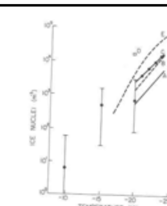
Homogeneous nucleation

- *Homogeneous nucleation* – freezing of a water droplet that contains no foreign particles
  - Ice embryo must exceed a critical size to produce a decrease in total energy and allow entire droplet to freeze
  - If critical size is not reached, ice embryo breaks up and cloud droplet does not freeze
  - Number and sizes of embryos increases with decreasing temperature
  - Homogeneous nucleation occurs
    - ~ -36°C for droplets between 20 and 60 microns in radius
    - ~ -39°C for droplets smaller than 20 microns in radius
  - At –40°C, water is usually frozen

Heterogeneous nucleation

- *Heterogeneous nucleation* – Freezing of a droplet that contains a foreign particle known as a freezing nucleus
- Analogous to cloud droplet formation, freezing nucleus allows water to freeze by decreasing the energy needed to move from the water to ice phase
- Allows droplets to freeze at higher temperatures than homogeneous nucleation (but not necessarily 0°C)

Heterogeneous nucleation



Wallace and Hobbs (1977)

- The effectiveness of potential ice nuclei is dependent on
  - Molecular spacing and crystal structure - similar to ice is best
  - Temperature – Activation is more likely as temperature decreases
- Ice nuclei concentration increases as temperature decreases
- Best ice nuclei are organic and insoluble in water (e.g., clay)

Heterogeneous nucleation

- On average, the number of ice nuclei per liter of air is given by an empirical relationship

$$\ln N = a(T_1 - T)$$
$$N = number\_of\_nuclei$$
$$a = 0.3 - 0.8$$
$$T = 253K$$

- For a=0.6, the ice nuclei concentration increases by a factor of 10 for every 4°C fall in temperature
- Only one particle in 10^8 acts as a ice nuclei at –20°C

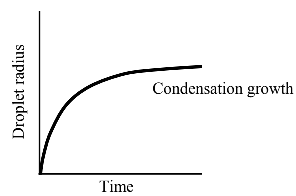
Ice multiplication

- There are relatively few ice nuclei in clouds compared to the number of ice particles
- How do we get large numbers of ice particles?
  - Ice multiplication – creation of large numbers of ice particles through
    - Mechanical fracturing of ice crystals during evaporation
    - Shattering of large drops during freezing
    - Splintering of ice during riming (Hallet-Mossop Process)

Formation of precipitation

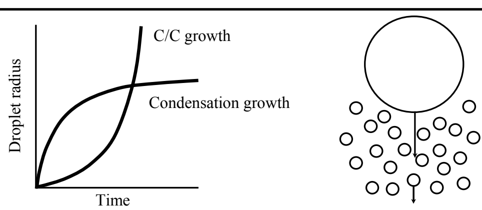
- Mechanisms for hydrometeor growth
  - Warm cloud processes
    - Condensation
    - Collision-coalescence
  - Cold cloud processes
    - Vapor deposition (Bergeron-Findeisen process)
    - Riming/accretion
    - Aggregation

Condensation



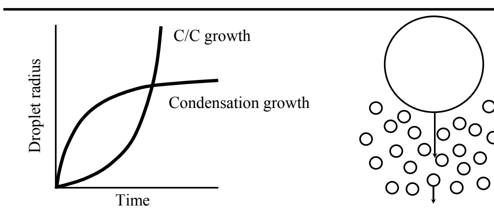
- Droplet growth by condensation is initially rapid, but diminishes with time
- Condensational growth too slow to produce large raindrops

Collision-coalescence



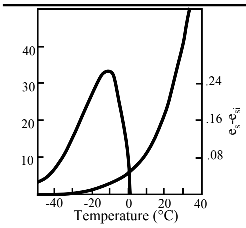
- Growth of small droplets into raindrops is achieved by *collision-coalescence*
- Fall velocity of droplet increases with size
- Larger particles sweep out smaller cloud droplets and grow

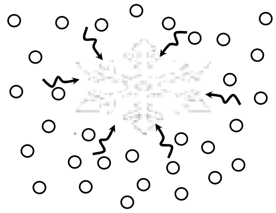
The warm cloud rain process



- Cloud droplet growth initially dominated by condensation
- Growth into raindrops dominated by collision-coalescence
- Most effective in maritime clouds
  - small concentrations of large cloud droplets (due to fewer CCN)

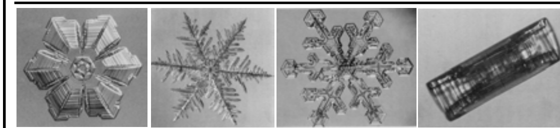
Vapor deposition (Bergeron-Findeisen Process)





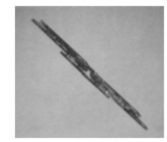
- Saturation vapor pressure for ice is lower than that for water
- Air is near saturation for water, but is supersaturated for ice
- Ice crystals/snowflakes grow by vapor deposition
- Cloud droplets may lose mass to evaporation

Vapor deposition (Bergeron-Findeisen Process)



Sector plate | Stellar dendrite | Dendritic sector plate | Hollow column

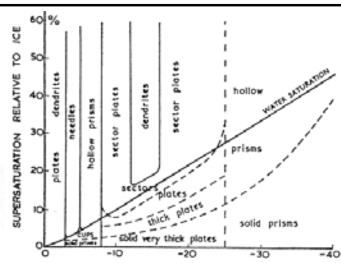
Snowcrystals.net



Needle

- *Habits* – types of ice crystal shapes created by vapor deposition)

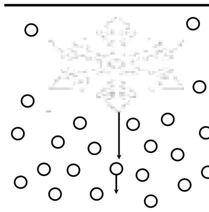
Vapor deposition (Bergeron-Findeisen Process)

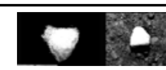


Snowcrystals.net

- Habit type is a function of
  - Temperature
  - Supersaturation relative to ice

Accretion (riming)





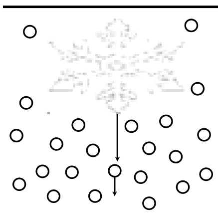
Graupel (UCLA)

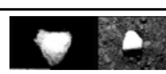
Hexagonal | Lump | Cone

Magono and Lee (1966)

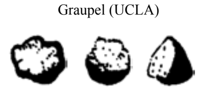
- Growth of a hydrometeor by collision with supercooled cloud drops that freeze on contact
- *Graupel* – Heavily rimed snow particles
  - 3 types: cone, hexagonal, lump

Accretion (riming)





Graupel (UCLA)

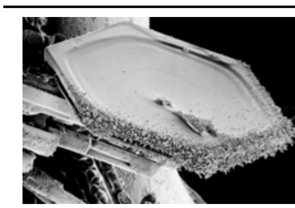


Hexagonal | Lump | Cone

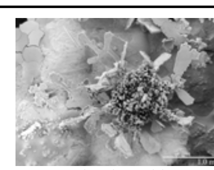
Magono and Lee (1966)

- Favored by
  - Warmer temperatures (more cloud liquid water, less ice)
  - Maritime clouds (fewer, but bigger, cloud droplets)
  - Strong vertical motion (larger cloud droplets lofted, less time for droplet cooling and ice nuclei activation)

Accretion (riming)



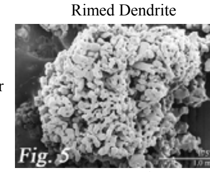
Rimed Plate



Rimed Dendrite

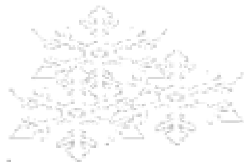
USDA Beltsville Agricultural Research Center

"Riming is not good for skiing"
- Jim Steenburgh



Graupel

Aggregation

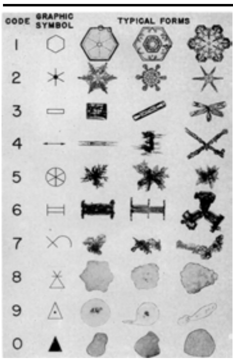


- Ice particles colliding and adhering with each other
- Can occur if their fall speeds are different
- Adhering is a function of crystal type and temperature
  - Dendrites tend to adhere because they become entwined
  - Plates and columns tend to rebound
  - Crystal surfaces become stickier above –5°C

The cold cloud precipitation process

- Condensational growth of cloud droplets
- Some accretional growth of cloud droplets
- Development of mixed phase cloud as ice nuclei are activated and ice multiplication process occurs
- Crystal growth through Bergeron-Findeisen process
  - Creates pristine ice crystals
  - Most effective at –10 to –15 C
- Other possible effects
  - Accretion of supercooled cloud droplets onto falling ice crystals or snowflakes
    - Snowflakes will be less pristine or evolve into graupel
    - Favored by
      - Warm temperatures (more cloud liquid water)
      - Maritime clouds (bigger cloud droplets)
      - Strong vertical motion
  - Aggregation
    - Entwining or sticking of ice crystals

Resulting solid precipitation types (International Commission on Snow and Ice)



Plates
Stellar crystals
Columns
Needles
Spatial dendrites
Capped columns
Irregular particles
Graupel
Sleet
Hail

Depositional Growth (Plates through Capped columns)

Riming (Irregular particles, Graupel)

Sleet: Refreezing of melted snow

Hail: "Big-time" riming

Summary

- Precipitation is not produced solely by condensation
- A cloud condensation nuclei is needed to initially help cloud droplets grow
- Collision-coalescence is needed for cloud droplets to grow into rain if cloud >0°C
- In mixed phase clouds
  - Mix of ice crystals and supercooled liquid water
  - Ice crystals form when cloud droplets are activated by an ice nuclei or through ice multiplication
  - Ice crystals grow "at expense" of cloud drops (Bergeron-Findeisen)
  - Accretion can increase the density of falling snow and SWE at ground
  - Aggregation can further increase hydrometeor size
- Most mid-latitude, continental rain is produced by mixed-phase clouds and involve ice-phase processes