

The background of the slide is a light blue gradient with several realistic water droplets of various sizes scattered across it. The droplets have highlights and shadows, giving them a three-dimensional appearance.

FORMATION OF CLOUD DROPS

OVERVIEW OF CHAPTER 6 FROM
R. R. ROGERS & M. K. YAU: A SHORT COURSE IN CLOUD PHYSICS

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Liquid drops

- Air ascend → droplets form from vapor
 - Homogeneous nucleation
 - Requires huge supersaturation
 - Heterogeneous nucleation
 - On condensation nuclei
 - Relative humidity barely exceeds 100%

Drops below 0°C

- Cloud ascend → droplets cooled below 0°C → supercooled
 - Homogeneous freezing
 - Requires low temperatures (−40°C)
 - Heterogeneous freezing
 - On ice nuclei
 - Very small amount
 - Supercooling down to −15°C

Cloud

- Tiny droplets
 - Several hundred / cm^3
 - $r \approx 10 \mu\text{m}$
- General growth
- Same size – same falling speed

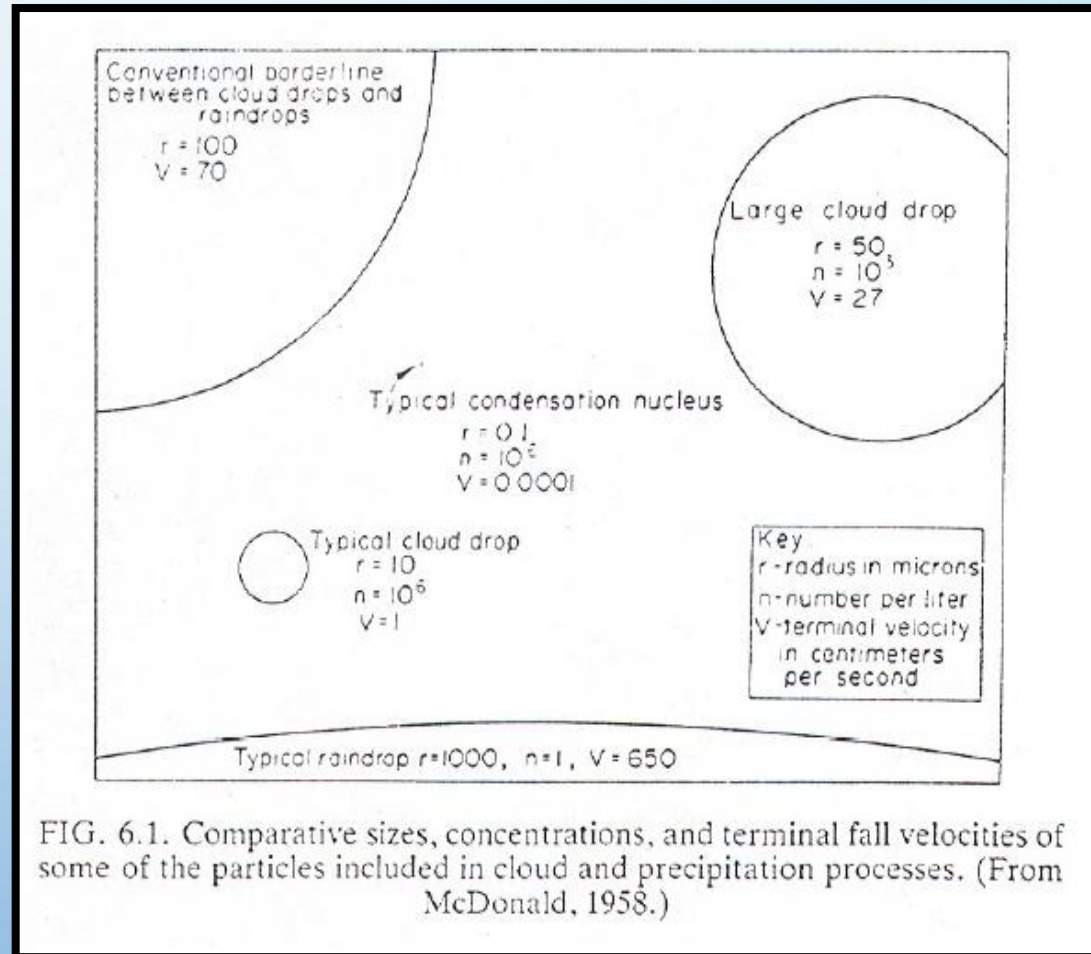


FIG. 6.1. Comparative sizes, concentrations, and terminal fall velocities of some of the particles included in cloud and precipitation processes. (From McDonald, 1958.)

Precipitation

- Cloud population become unstable → precipitation develops
 - Some drops grow
- Cloud microstructure become unstable
 - Collision & coalescence
 - Water droplet + ice crystal
- If $r \leq 18 \mu\text{m}$ → small fraction collide
 - Clouds have larger drops

○ Difference in equilibrium vapor pressure

- Ice crystals + much supercooled droplets → unstable
- Eq. v. pr. over ICE < Eq. v. pr. over WATER (same temperature)
- Ice crystals grow, drops evaporate
- Vapor transfer depends on the difference in Eq. v. pr.
 - Most effective on -15°C
- Ice crystals grow larger than drops → begin to fall → collision

Collide with ice crystal

- Ice crystal + ice crystal → snowflake
- Ice crystal + water → graupel/hail
- Above 0°C melting can occur
- Quick growth process

(In)stability

- Problem: How can a small droplet become stable?
 - Need to exceed a critical size (r_c)
 - r_c is determined by the circumstances
 - Formed by homo- / heterogeneous nucleation
 - (partial pressure of water vapor)
 - Evaporation
 - Temperature
 - Surface tension

Equilibrium vapor pressure

- Condensation = Evaporation
- Eq. v. press. – curvature → Kelvin – equation

$$e_s(r) = e_s(\infty) \exp\left(\frac{2\sigma}{rR_v\rho_L T}\right)$$

- $e_s(r)$: equilibrium vapor pressure over a droplet
- $e_s(\infty)$: equilibrium vapor pressure far from a droplet
- σ : surface tension
- R_v : gas constant for water vapor
- ρ_L : density

Critical size

- Growth rate $\sim e - e_s(r)$ difference
- Critical size: $e - e_s(r) = 0$

$$r_c = \frac{2\sigma}{R_v \rho_L T \ln S}$$

- $S = \frac{e}{e_s(\infty)}$: saturation ratio
- e : actual ambient vapor pressure

Critical & supercritical size

TABLE 6.1. Radii and Number of Molecules in Droplets of Pure Water in Equilibrium with the Vapor at 0°C

Saturation ratio S	Critical radius r_c (μm)	Number of molecules n
1	∞	∞
1.01	1.208×10^{-1}	2.468×10^8
1.10	1.261×10^{-2}	2.807×10^5
1.5	2.964×10^{-3}	3.645×10^3
2	1.734×10^{-3}	730
3	1.094×10^{-3}	183
4	8.671×10^{-4}	91
5	7.468×10^{-4}	58
10	5.221×10^{-4}	20

- Small droplet requires high supersaturation to be stable
- If a critical sized droplet captures a molecule, becomes supercritical
 - $e_s(r)$ decreases with increasing size
 - rate of growth increase
 - grow spontaneously

Types of condensation nuclei

- Affinity for water
 - Hygroscopic $\sim\sim>$ rate of droplet formation
 - Neutral
 - Hydrophobic $\sim\sim>$ nucleation is more difficult
- On soluble particles
 - Lower supersaturation required

Effect of dissolved substance

- Tends to lower the eq. v. pr. of a liquid
- Raoult's Law:

$$\frac{e'}{e_s(\infty)} = \frac{n_0}{n + n_0}$$

- e' : new equilibrium vapor pressure
 - n_0 : molecules of water
 - n : molecules of solute
- For dilute solutions ($n \ll n_0$): $\frac{e'}{e_s(\infty)} = 1 - \frac{n}{n_0}$

Degree of ionic dissociation

- Add an extra factor (i):

$$n = \frac{iN_0M}{m_s}$$

- Number of water molecules (n_0):

$$n_0 = \frac{N_0m}{m_v}$$

- n : number of effective ions in solute

- N_0 : Avogadro's number

- M : mass of solute

- m_s : molecular weight of a solute

- m_v : molecular weight of vapor

$$\frac{e'}{e_s(\infty)} = 1 - \frac{b}{r^3}$$

where $b = \frac{3im_vM}{4\pi\rho_L m_s}$ Mass of water:

$$m = \frac{4}{3}\pi r^3 \rho_L$$

Kelvin's equation & solution effect

$$\frac{e'(r)}{e_s(\infty)} = \left(1 - \frac{b}{r^3}\right) e^{\frac{a}{r}}$$

$$\bullet a = \frac{2\sigma}{R_v \rho_L T}$$

$$\bullet b = \frac{3im_v M}{4\pi\rho_L m_s}$$

- For r not too small a good approximation:

$$\frac{e'(r)}{e_s(\infty)} = 1 + \frac{a}{r} - \frac{b}{r^3}$$

Köhler curve

- Solution effect dominates when r is small ($1 - \frac{b}{r^3}$)
- If relative humidity increases, drop will grow till equilibrium
- Critical saturation ratio (S^*)
 - over 100% (eg.: 0.6% supersat.)
- Critical radius (r^*) (eg: 0,13 μm)
- Beyond r^* equilibrium is unstable

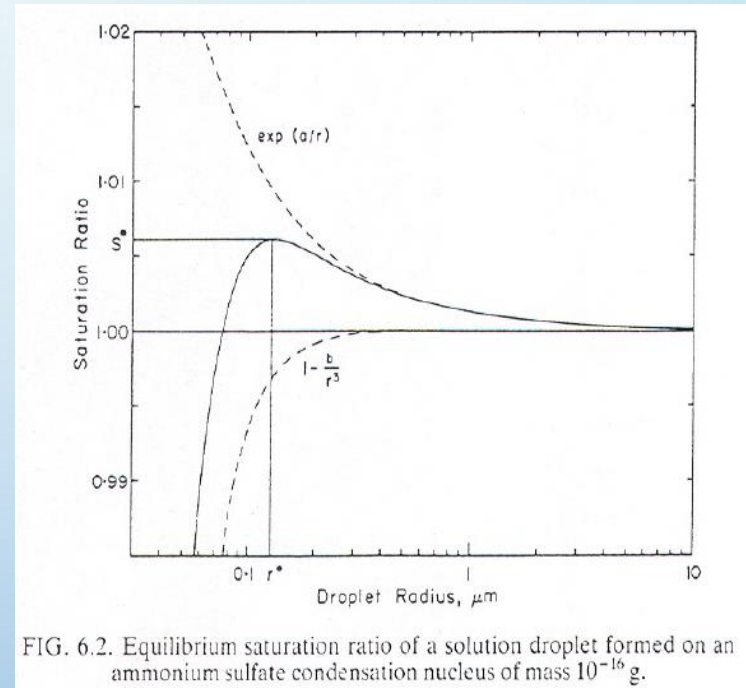


FIG. 6.2. Equilibrium saturation ratio of a solution droplet formed on an ammonium sulfate condensation nucleus of mass 10^{-16} g.

$$r^* = \sqrt{\frac{3b}{a}} \quad S^* = 1 + \frac{b}{4a^3/27b}$$

THANK YOU FOR YOUR ATTENTION

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