Cloud microphysics

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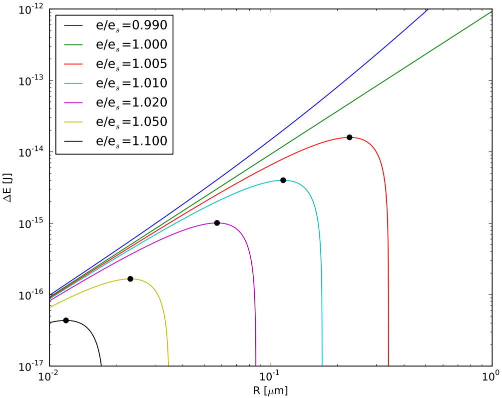
Overview of cloud physics lecture

- Atmospheric thermodynamics
    - gas laws, hydrostatic equation
    - 1st law of thermodynamics
    - moisture parameters
    - adiabatic / pseudoadiabatic processes
    - stability criteria / cloud formation
- Microphysics of warm clouds
    - nucleation of water vapor by condensation
    - growth of cloud droplets in warm clouds (condensation, fall speed of droplets, collection, coalescence)
- Microphysics of cold clouds
    - homogeneous nucleation
    - heterogeneous nucleation
    - contact nucleation
    - crystal growth (from water phase, riming, aggregation)
    - formation of precipitation
- Observation of cloud microphysical properties
- Parameterization of clouds in climate and NWP models

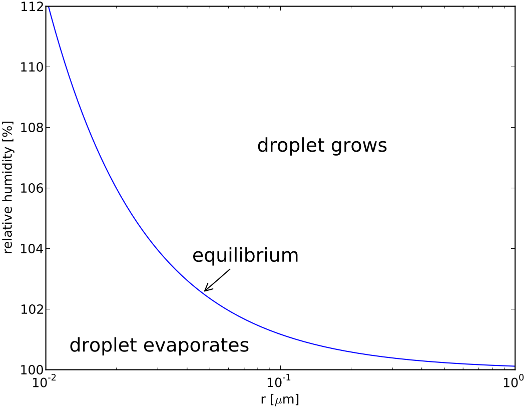
Energy difference due to formation of droplet

ΔE = surface energy of droplet - Gibbs free energy due to condensation

$$\Delta E = 4\pi R^2 \sigma - \frac{4}{3}\pi R^3 nkT \ln \frac{e}{e_s}$$



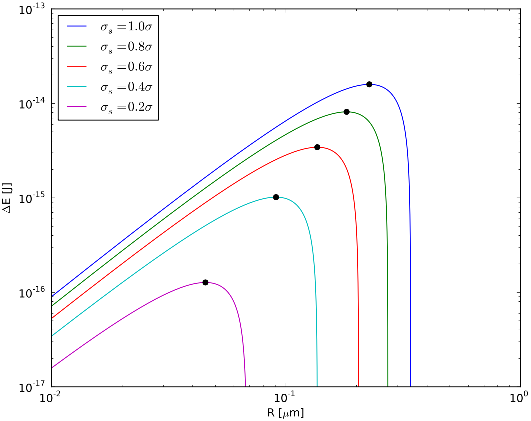
Kelvin equation



Kelvin equation

$$r = \frac{2\sigma}{nkT \ln \frac{e}{e_s}}$$

Impact of surface tension on energy balance



Surface tension is reduced when soluble aerosol (e.g. detergent) is added to droplet.

Calculation for 0.5% supersaturation, T=293 K.

Effect of solute concentration on surface tension

- sugars have little or no effect
- inorganic salts increase surface tension
- surfactants and alcohols decrease surface tension

Question: Why do salts also act as condensation nuclei?

Raoult's law

Vapor pressure of an ideal solution depends on mole fraction of the component present in the solution

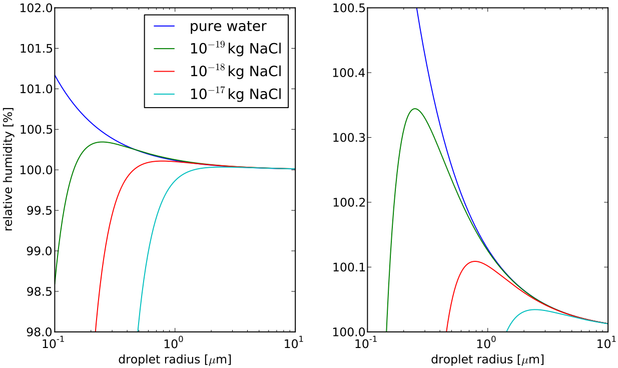
$$\frac{e'}{e} = f$$

e' – saturation water vapor pressure adjacent to solution droplet containing a mole fraction f of pure water
e – saturation water vapor pressure adjacent to pure water droplet
f – number of moles of pure water divided by total number of moles

$\Rightarrow$ saturation water vapor pressure is reduced when aerosol is solved in droplet

Köhler curves

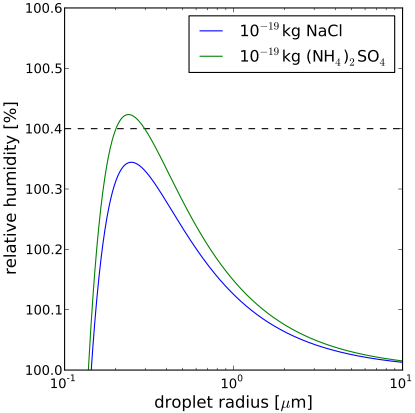
$$\frac{e}{e_s} = \left(\exp\frac{2\sigma'}{n'kTr}\right)\left(1+\frac{imM_w}{M_s\left(\frac{4}{3}\pi r^3\rho' - m\right)}\right)^{-1}$$



Reduction of saturation vapor pressure explains why salts may act as condensation nuclei.

Köhler curves

$$\frac{e}{e_s} = \left(\exp\frac{2\sigma'}{n'kTr}\right)\left(1+\frac{imM_w}{M_s\left(\frac{4}{3}\pi r^3\rho' - m\right)}\right)^{-1}$$



At 0.4% supersaturation of the ambient air, the solution droplet containing NaCl becomes activated, the solution droplet containing the same mass of $(NH_4)_2SO_4$ remains unactivated (haze droplet) ⇒ NaCl more efficient condensation nucleus than $(NH_4)_2SO_4$

Growth rate and size distribution

- growing droplets consume water vapor faster than it is made available by cooling and supersaturation decreases
- haze droplets evaporate, activated droplets continue to grow by condensation

growth rate of water droplet

$$\frac{dr}{dt} = G_l S \frac{1}{r}$$

- smaller droplets grow faster than larger droplets
- sizes of droplets in cloud become increasingly uniform, approach monodisperse distribution

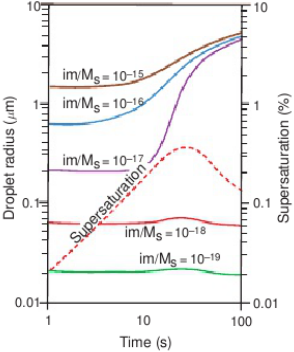


Fig. 6.16 Theoretical computations of the growth of cloud condensation nuclei by condensation in a parcel of air rising with a speed of 60 cm s^{-1}. A total of 500 CCN cm^{-1} was assumed with im/M_s values [see Eq. (6.8)] as indicated. Note how the droplets that have been activated (brown, blue, and purple curves) approach a monodispersed size distribution after just 100 s. The variation with time of the supersaturation of the air parcel is also shown (dashed red line). [Based on data from *J. Meteor.* **6**, 143 (1949).]

Figure from Wallace and Hobbs

Sizes of cloud droplets

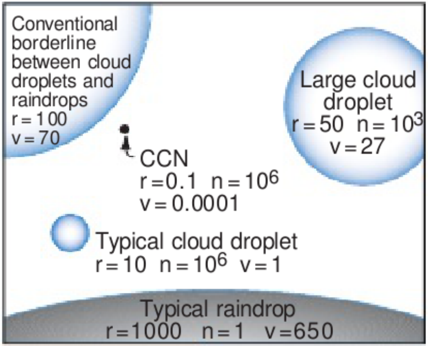


Figure from Wallace and Hobbs

- growth by condensation alone can not produce raindrops with radii of several mm !

Collision efficiency

Collision efficiency

$$E = \frac{y^2}{r_1^2 + r_2^2}$$

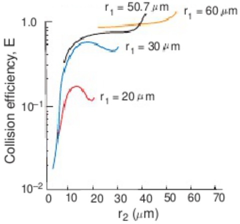


Fig. 6.20 Calculated values of the collision efficiency, E, for collector drops of radius r_1 with droplets of radius r_2. [Adapted from H. R. Pruppacher and J. D. Klett, *Microphysics of Clouds and Precipitation*, Kluwer Academic Pub., 1997, Fig. 14-6, p. 584, Copyright 1997, with kind permission of Springer Science and Business Media. Based on *J. Atmos. Sci.* **30**, 112 (1973).]

Figure from Wallace and Hobbs

- E increases when size of collector drop r_1 increases
- E small for $r_1 < 20\mu$m
- $r_1 \gg r_2$: E small because small droplets follow streamlines around collector drop
- E increases with increasing r_2 until $r_2/r_1 \approx$ 0.6–0.9
- r_2/r_1 >0.6–0.9: E decreases because relative velocity between droplets becomes small
- r_2/r_1 ≈1: strong interaction between droplets, E increases again

Coalescence

Coalescence: Droplet is captured when it collides with larger droplet

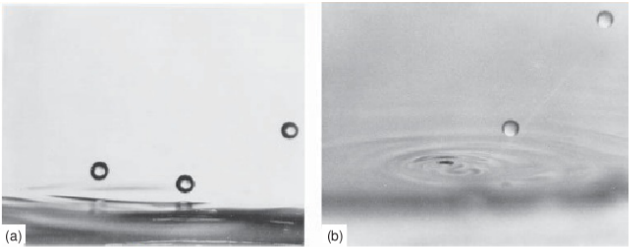


Fig. 6.21 (a) A stream of water droplets (entering from the right), about 100 μm in diameter, rebounding from a plane surface of water. (b) When the angle between the stream of droplets and the surface of the water is increased beyond a critical value, the droplets coalesce with the water. [Photograph courtesy of P. V. Hobbs.]

Figure from Wallace and Hobbs

Coalescence

- droplets are not always captured, they may bounce off one another
- this happens because air becomes trapped between surfaces and droplets deform without touching
- droplet may rebound on cushion of air
- if cushion of air is squeezed out before rebounce occurs, droplets touch $\Rightarrow$ Coalescence occurs

Coalescence efficiency

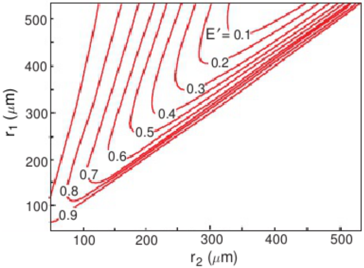


Fig. 6.22 Coalescence efficiencies E' for droplets of radius r_2 with collector drops of radius r_1 based on an empirical fit to laboratory measurements. [Adapted from *J. Atmos. Sci.* **52**, 3985 (1995).]

Figure from Wallace and Hobbs

Coalescence efficiency

E'=fraction of collisions that result in coalescence

- E' large for $r_2 \ll r_1$
- E' initially decreases as r_2 increases
- as r_2 approaches r_1, E' increases sharply

Coalescence efficiency

Explanation:

- whether coalescence occurs depends on relative magnitude of impact energy to surface energy of water
- energy ratio provides measure of deformation of collector drop due to impact
- this determines how much air is trapped
- maximum tendency for bouncing at intermediate size ratio

Remark: E' increases in presence of electric field

Collection efficiency

$$E_c = E \cdot E'$$

Continuous collection model

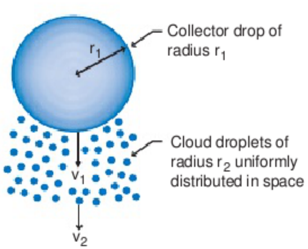


Fig. 6.23 Schematic illustrating the continuous collection model for the growth of a cloud drop by collisions and coalescence.

Figure from Wallace and Hobbs

- collector drop with radius r_1 and terminal velocity v_1
- drop falls in still air through cloud of equal sized droplets with r_2 and v_2
- droplets are uniformly distributed and collected uniformly by all collector drops of a given size

Deformation of falling drops and fragmentation

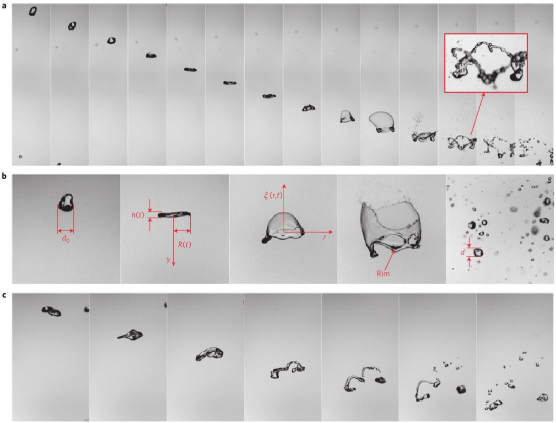


Figure 2 | Topological changes of falling drops and fragmentation. Top row: series of events of the fragmentation of a $d_0 = 6$ mm water drop falling in an ascending stream of air. The time interval between each image is $\Delta t = 4.7$ ms. The sequence shows first the flattening of the drop into a pancake shape, the inflation of a bag bordered by a thicker corrugated rim, its break-up and the destabilization of the rim itself (highlighted in the inset), leading to disjointed drops distributed in size. Middle row: a similar series defining the initial diameter d_0, the bag thickness $h(t)$, its radius $R(t)$ and shape $\xi(r,t)$, and the final drop size d. Bottom row: the formation of a bag is not mandatory for the initial drop to break up. However, its fragmentation is always preceded by a change of topology into a ligament shape, which often occurs without bag inflation. The sequence is for $d_0 = 6$ mm and $\Delta t = 7.9$ ms.

Figure from Villermaux and Bossa (2009)

Gap between condensational and collectional growth

- condensational growth
  - slows appreciably as droplet radius approaches $\sim 10\mu$m
  - tends to produce monodisperse size distribution
  - droplets then have similar fall speeds $\Rightarrow$ collisions become unlikely
- collectional growth
  - conditions: a few reasonably efficient collector drops (i.e. r$>$ 20μm) cloud deep enough and contains sufficient amount of water
- Question 1: How do the collector drops initially form

Continuous collection model

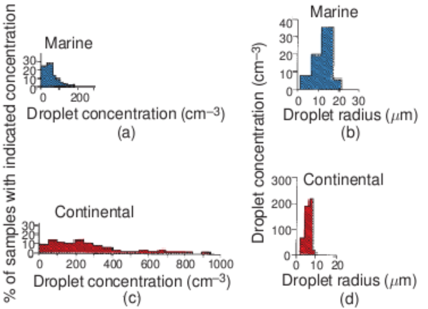


Fig. 6.7 (a) Percentage of marine cumulus clouds with indicated droplet concentrations. (b) Droplet size distributions in a marine cumulus cloud. (c) Percentage of continental cumulus clouds with indicated droplet concentrations. (d) Droplet size distributions in a continental cumulus cloud. Note change in ordinate from (b). [Adapted from P. Squires, "The microstructure and colloidal stability of warm clouds. Part I—The relation between structure and stability," *Tellus* **10**, 258 (1958). Permission from Blackwell Publishing Ltd.]

Figure from Wallace and Hobbs

Question 2:
How do the broad size distributions form that are commonly measured?

Giant cloud condensation nuclei (GCCN)

GCCN are wettable particles with radius $> 3\mu$m
$\Rightarrow$ may act as embryos for formation of collector drops

- 1 GCCN/l can account for formation of precipitation sized particles, even in continental clouds
- 0.1–10 GCCN/l may transform non-precipitating stratocumulus cloud into precipitating cloud

Turbulence

Effect of turbulence on droplet growth

- turbulence enhances collision efficiency
- turbulence produces fluctuations in supersaturation and thereby enhances condensational growth

Example: inhomogeneous mixing

finite blobs of unsaturated air mix with nearly saturated blobs
$\Rightarrow$ evaporation of some droplets of all sizes
$\Rightarrow$ overall concentration of droplets reduced
$\Rightarrow$ remaining drops may grow faster

Turbulence

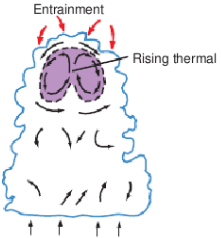


Fig. 6.12 Schematic of entrainment of ambient air into a small cumulus cloud. The thermal (shaded violet region) has ascended from cloud base. [Adapted from *J. Atmos. Sci.* **45**, 3957 (1988).]

Figure from Wallace and Hobbs

- downdrafts are formed when saturated air near cloud top mixes with dry environmental air:
  - evaporation of drops produces cooling, cool air descends
- Larger drops may be mixed into downdrafts from surrounding undiluted air
- when downdraft is transformed to updraft, larger droplets will further increase in size
- with sufficient entrainment of air and vertical cycling, a broad droplet size spectrum may be produced

Radiative broadening

- when droplet grows by condensation, it is warmer than environmental air ⇒ droplet will lose heat by radiation
- saturation vapor pressure of droplet is lower, and droplet grows faster than predicted if radiation is neglected
- loss of heat by radiation proportional to surface area of droplet, therefore radiation effect greater the larger the drop
- radiation enhances growths of potential collector drops

Stochastic collection

continuous collection model

- collector drop collides in continuous and uniform fashion with smaller cloud droplets which are uniformly distributed in space
- therefore collector drops of the same size grow at the same rate if they fall through the same cloud of droplets

stochastic (statistical) collection model

- treats collisions as individual events, distributed statistically in time and space

Stochastic collection

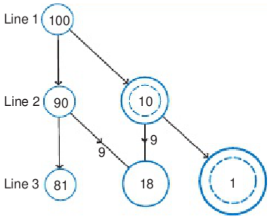


Fig. 6.24 Schematic diagram to illustrate broadening of droplet sizes by statistical collisions. [Adapted from *J. Atmos. Sci.* **24**, 689 (1967).]

Figure from Wallace and Hobbs

- Line 1: 100 droplets start at the same size
- Line 2: after some time 10 droplets have collided with other droplets
- Line 3: second collisions produce 3 sizes

Stochastical model results in broad size distributions

Shape of raindrops

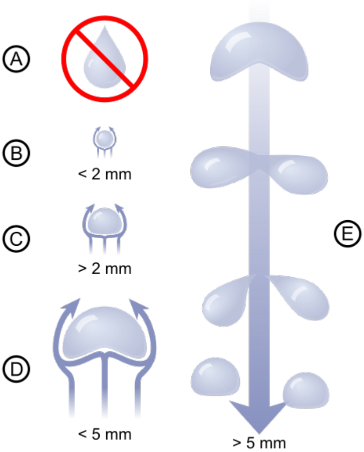


Figure from Wikipedia

- as raindrop size increases it becomes flattened, gradually changes shape from spherical to increasingly parachute
- if initial radius $>$ 2.5mm parachute becomes inverted bag with toroidal ring of water around lower rim
- when drop bursts to produce fine spray of droplets, toroidal ring breaks up into large drops

Collision between raindrops

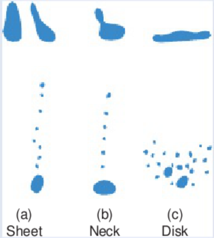

(a) Sheet (b) Neck (c) Disk

Fig. 6.27 Schematic illustrations of three types of breakup following the collision of two drops. [Adapted from *J. Atmos. Sci.* **32**, 1403 (1975).]

Figure from Wallace and Hobbs

breakup by collisions more likely than bag breakup ?
probabilities of 3 main types of breakup following collision

- sheets: 55%
- necks: 27%
- disks: 18%

Size distribution of raindrops

Measurements of the size distribution of raindrops that reach the ground can often be fitted to the same size distribution function:

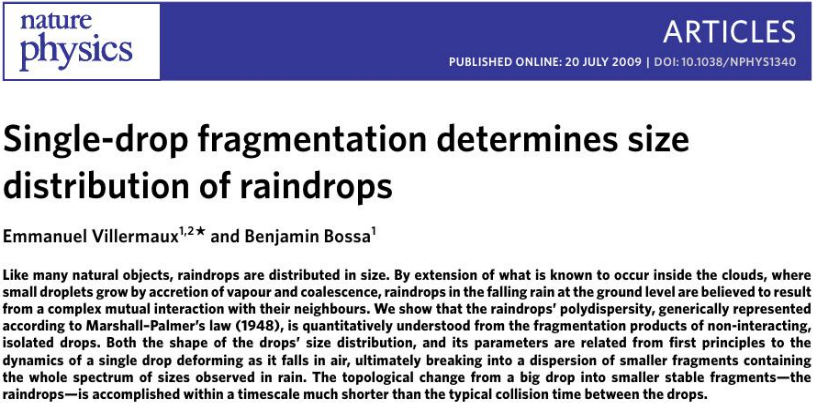
Marshall-Palmer distribution

$$N(D) = N_0 \exp -\Lambda D$$

$N(D)dD$ – number of drops per unit volume with diameters between D and $D + dD$
N_0 and Λ – empirical fitting parameters

N_0 almost const., Λ varies with rainfall rate

Size distribution of raindrops



nature physics

ARTICLES

PUBLISHED ONLINE: 20 JULY 2009 | DOI: 10.1038/NPHYS1340

Single-drop fragmentation determines size distribution of raindrops

Emmanuel Villermaux[1,2]★ and Benjamin Bossa[1]

Like many natural objects, raindrops are distributed in size. By extension of what is known to occur inside the clouds, where small droplets grow by accretion of vapour and coalescence, raindrops in the falling rain at the ground level are believed to result from a complex mutual interaction with their neighbours. We show that the raindrops' polydispersity, generically represented according to Marshall–Palmer's law (1948), is quantitatively understood from the fragmentation products of non-interacting, isolated drops. Both the shape of the drops' size distribution, and its parameters are related from first principles to the dynamics of a single drop deforming as it falls in air, ultimately breaking into a dispersion of smaller fragments containing the whole spectrum of sizes observed in rain. The topological change from a big drop into smaller stable fragments—the raindrops—is accomplished within a timescale much shorter than the typical collision time between the drops.

Current cloud research

Cloud research at Schneefernerhaus (Zugspitze),
DLR Oberpfaffenhofen, KIT Karlsruhe and MPI Göttingen

Film: “Rätsel am Himmel: Was Forscher aus den Wolken lesen”
BR, 6.11.2011, 23:15, Faszination Wissen
`http://www.br.de/fernsehen/bayerisches-fernsehen/sendungen/faszination-wissen/fawi-wolken100.html`