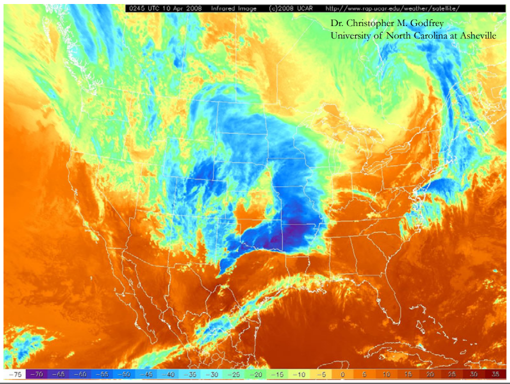
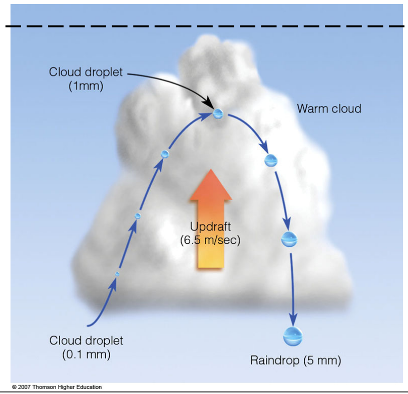
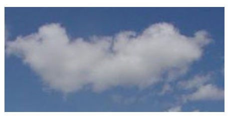
Warm Cloud Processes



Warm clouds lie completely below the 0° isotherm



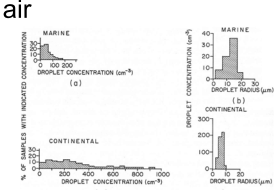
Some definitions



- Liquid water content (LWC)
  - Amount of liquid water per unit volume of air (g cm^{-3})
- Droplet concentration
  - Total number of water droplets per unit volume of air (# cm^{-3})
- Droplet spectrum
  - Size distribution of cloud droplets
  - Expressed as the number of droplets per cm^3 in various droplet size intervals

CCN observations in marine and continental clouds

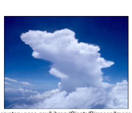
- Marine cumulus clouds
  - Most samples had droplet concentrations < 100 cm^{-3}
- Continental cumulus clouds
  - Droplet concentrations as high as 900 cm^{-3}
- Differences reflect higher concentrations of CCN in continental air



Effects of cloud condensation nuclei

- Marine and continental cumulus cloud LWCs are about the same
  - Higher droplet concentrations in continental cumulus must result in a *smaller* average droplet size

→Differences in the microstructure of marine and continental clouds have important consequences for the development of precipitation in warm marine and continental cumulus clouds.



Source: http://earthobservatory.nasa.gov/Library/Giants/Simpson/Images/convective_tower.jpg

Two ways to make big drops:

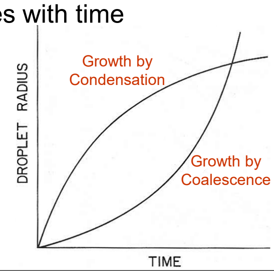
- In warm clouds, droplets can grow by
  - Condensation in a supersaturated environment
  - Collision and coalescence

Growth by condensation

Growth by condensation

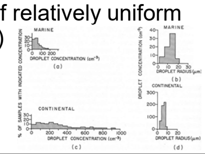
Growth by condensation

- For fixed supersaturation (S), droplets growing by condensation initially increase in radius very rapidly but their growth rate diminishes with time

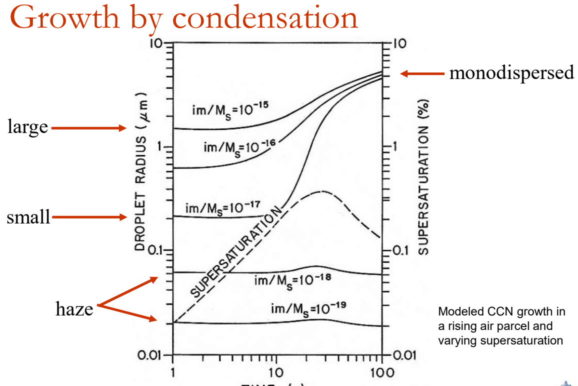


Growth by condensation

- Adiabatic cooling produces supersaturation for the initial formation of droplets
- Subsequent droplets consume water at a greater rate than the water is made available, so the supersaturation decreases
- The growth rate of activated aerosols by condensation is inversely proportional to radius: smaller droplets grow faster
- This results in a population of relatively uniform droplet size (*monodispersed*)



Growth by condensation

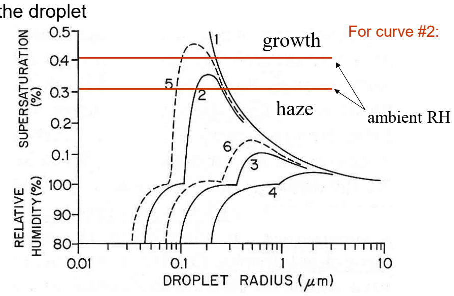


Modeled CCN growth in a rising air parcel and varying supersaturation

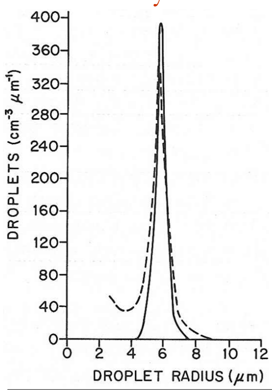
Note: im/M_S = effective number of kilomoles of salt in the droplet

Growth by condensation

- Once a cloud droplet has begun to grow spontaneously by condensation, it will continue to grow by this process as long as the ambient vapor pressure exceeds the vapor pressure over the droplet



Growth by condensation

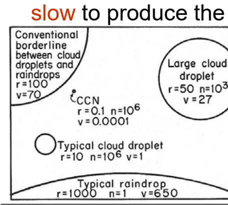


Comparison of predicted (solid) and observed (dashed) cloud droplet size distribution assuming growth by condensation.

Can growth by condensation alone explain how precipitation forms in warm clouds?

Growth by condensation

- Growth by condensation is slow when the droplet gets large
- For a cloud droplet 10 μm in radius to grow to a raindrop 1 mm in radius requires an increase in volume of *one millionfold!*
- Growth by condensation alone in warm clouds is too slow to produce the necessary size for raindrops



r = radius in μm

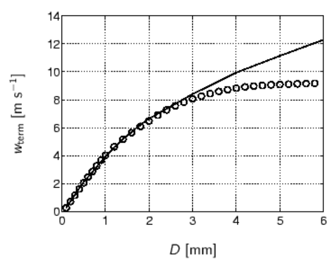
n = # per liter of air

v = terminal velocity in cm s^{-1}

Growth by collision and coalescence

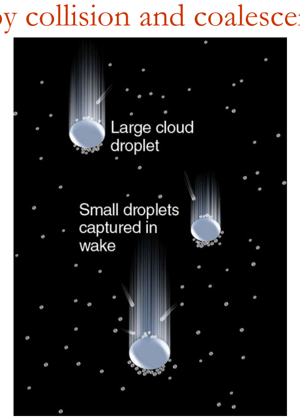
- Growth of droplets from the relatively small sizes achieved by condensation to the size of raindrops is achieved by collision and coalescence of droplets
  - Each droplet has a steady settling velocity as it falls under the influence of gravity through still air (*terminal fall speed*)
  - Larger droplets have a higher terminal fall speed and collide with smaller droplets

Terminal velocities of various drop sizes

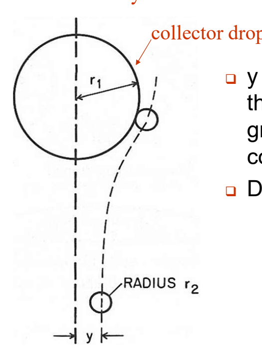


Terminal velocities based on an equation (line) and measurements (circles). Measurements from Gunn and Kinzer (1949).

Growth by collision and coalescence



Growth by collision and coalescence

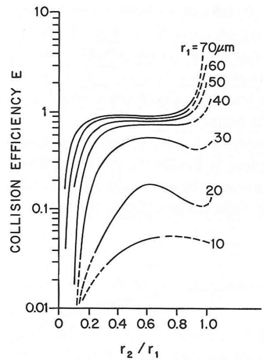


- y = critical distance such that the droplet just makes a grazing collision with the collector drop
- Define collision efficiency as

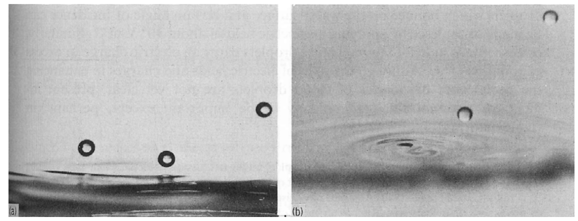
$$E = \frac{y^2}{(r_1 + r_2)^2}$$

Collision efficiency (E)

- For r_1 < 20 μm, collisions are inefficient
- For r_2/r_1 << 1
  - Droplets follow streamlines
- For larger r_2/r_1
  - Droplets follow straight lines
- For $r_2/r_1 \approx$ 0.6–0.9
  - Terminal velocities are similar
  - Relative velocity is small
- For $r_2/r_1 \approx$ 1
  - Drops strongly interact
  - Wake effects allow for E > 1

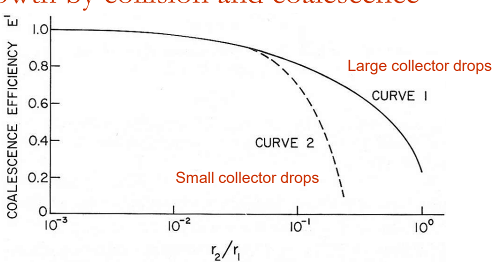


Growth by collision and coalescence



- A collision does not guarantee that the droplet will be captured (i.e., that coalescence will occur)
- Droplets can rebound if air becomes trapped between them!

Growth by collision and coalescence



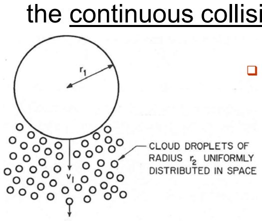
- Define coalescence efficiency E′ as the fraction of collisions resulting in coalescence
  - E′ falls off sharply as the sizes of the drops approach one another

Coalescence efficiency E′

- Influence of electric fields
  - Enhanced by the presence of an electric field
  - Aided if the impacting droplets carry an electric charge in excess of about 10^{-14} C
  - Likely not important except in thunderstorms

Growth by collision and coalescence

- Growth rate due to collision-coalescence in the continuous collision model



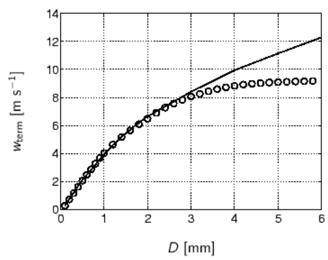
- Define the following:
  - Collection efficiency E_C = EE′
  - M = mass of collector drop
  - w_ℓ = liquid water content (kg m^{-3}) of cloud droplets of radius r_2
  - v = terminal velocity
  - ρ_ℓ = density of liquid water

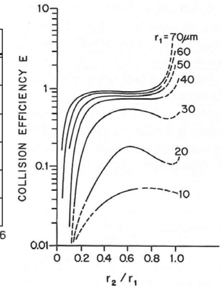
Rate of increase in the mass of the collector drop due to collisions

Rate of increase in the radius of the collector drop due to collisions

Growth by collision and coalescence

- v_1 increases as r_1 increases
- E increases with increasing r_1



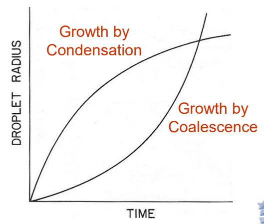


Growth by collision and coalescence

- v_1 increases as r_1 increases
- E increases with increasing r_1

  → Growth rate increases with increasing radius of the collector drop

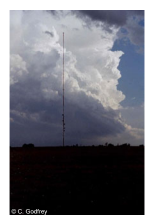
Growth by condensation is initially dominant, but beyond a certain radius, growth by collisions dominates



Consider updrafts

- For a steady updraft velocity w:
  - Velocity of the collector drop is $w - v_1$
  - Velocity of the cloud droplets is $w - v_2$

  → Radius of the collector drop at height H above cloud base is r_H and at cloud base is r_0:



$$H = \frac{4\rho_l}{w_l}\left[\int_{r_0}^{r_H} \frac{w}{v_1 E} dr_1 - \int_{r_0}^{r_H} \frac{dr_1}{E}\right]$$

Consider updrafts

- Far above cloud base (H is large), $w > v_1$ and the drop grows by collisions as it is carried upward in the cloud
  - H increases as r_H increases
- As the drop grows, $w < v_1$ and the drop falls and grows as it falls (H decreases) eventually passing through the cloud base and reaching the ground as a raindrop…assuming it holds together

$$H = \frac{4\rho_l}{w_l}\left[\int_{r_0}^{r_H} \frac{w}{v_1 E} dr_1 - \int_{r_0}^{r_H} \frac{dr_1}{E}\right]$$

Call this Equation (1)

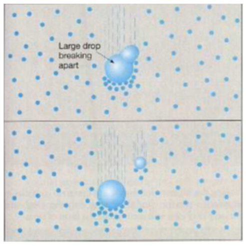
Growth by collision and coalescence

- Application of equation 1:
  - Given a cloud with $w_\ell = 1.0$ g m^{-3} of water (10 µm radius droplets) and an updraft velocity of w = 1.0 m s^{-1}
  - Initially small collector drop grows to a radius of about 0.15 mm in about 45 minutes as it travels upward to a height of 2.2 km
  - Over the next 15 minutes, the drop radius increases to 0.75 mm as it falls back to the cloud base (rain)
  - Change liquid water content of cloud to $w_\ell = 0.5$ g m^{-3} and an updraft velocity of 0.1 m s^{-1}: Collector drop rises to only 0.5 km and takes 2 h for it to fall to the cloud base with a radius of only 0.1 mm (drizzle)

Warm clouds with strong updrafts should produce rain in a shorter time than clouds with weak updrafts, but clouds with strong updrafts must be quite deep in order for raindrops to be produced.

Growth by collision and coalescence

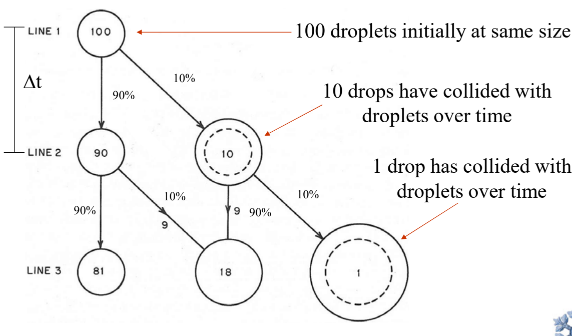
- Even after two droplets have coalesced, the motions set up in their combined mass may cause it to subsequently break up into several droplets.
  - The resulting fragments may then grow and break up again; such a chain reaction may enhance the precipitation.



Stochastic collision model

- More realistic than the continuous collision model
- Collisions are individual events, statistically distributed in time and space; droplets are not all experiencing continuous collisions

Stochastic collision model



Stochastic collision model

- Provides a mechanism for developing broad droplet size spectra from fairly uniform droplet sizes produced by condensation
- Reveals how a small fraction of the droplets in a cloud can grow much faster than average by statistically distributed collisions