OUTLINE

1. Nucleation of water droplets (6.1)

2. Microstructures of warm clouds (6.2)

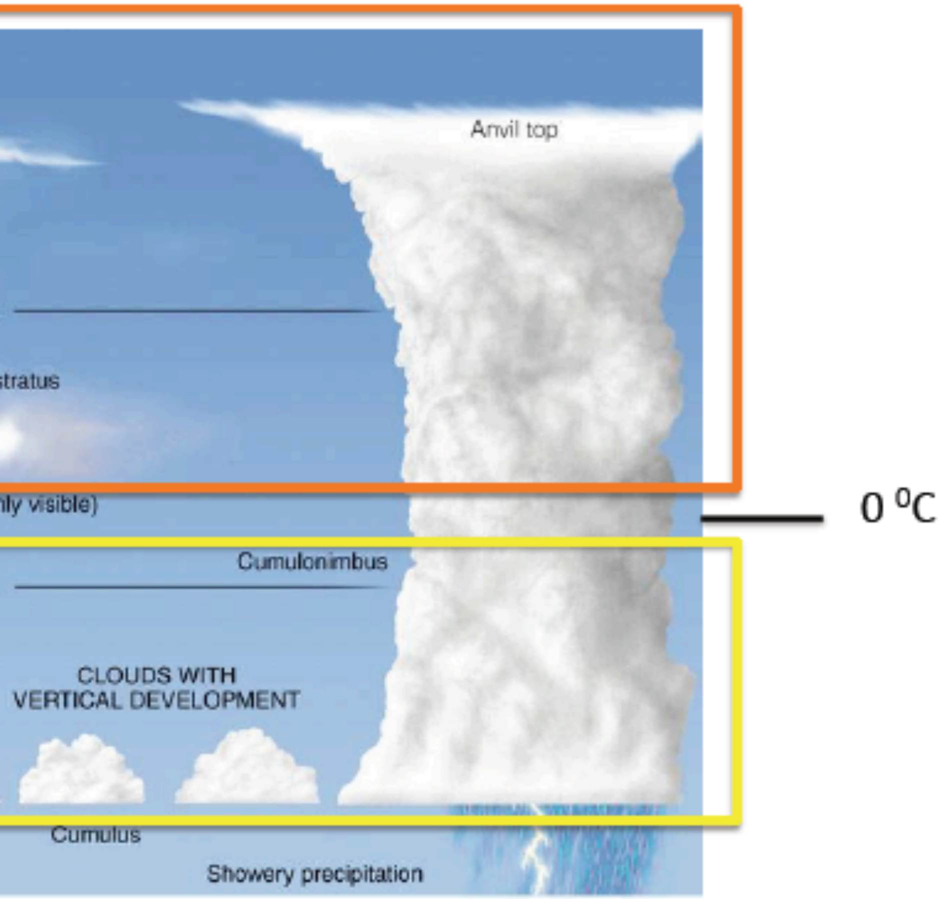
3. Cloud Liquid Water Content and Entrainment (6.3)

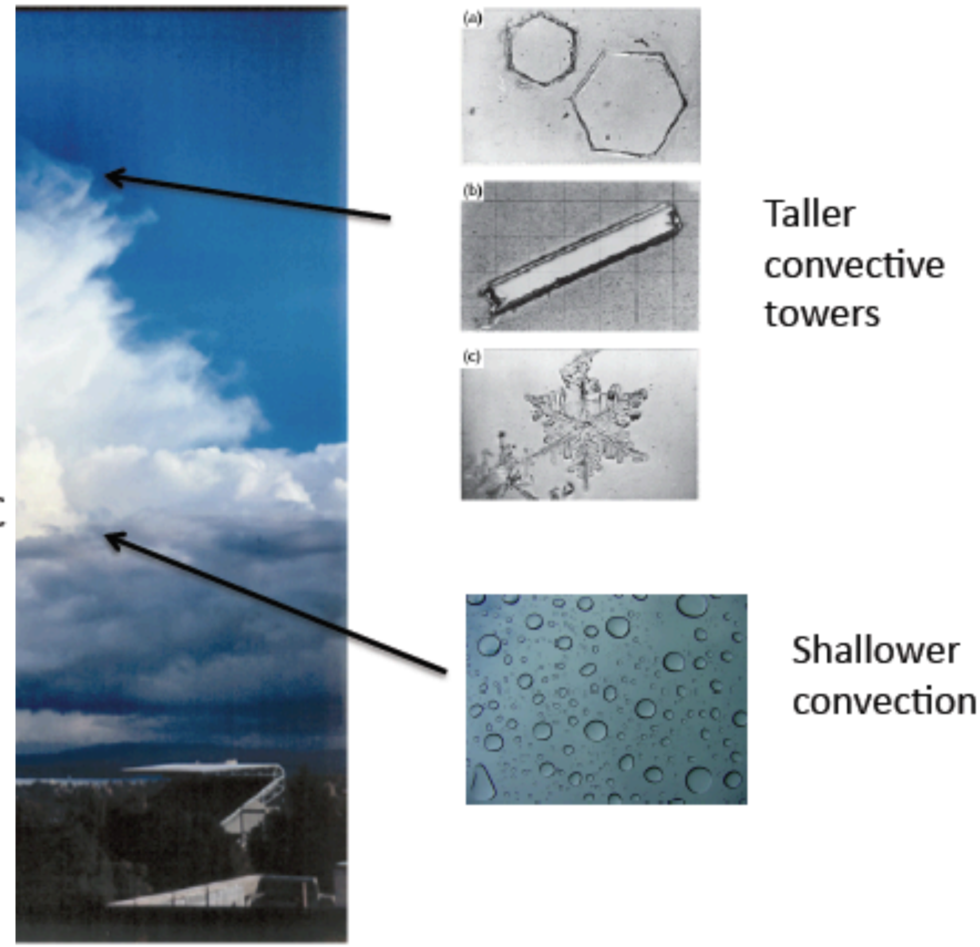
4. Growth of Water Droplets and Formation of Rain (6.4)

5. **Microphysics of Ice Clouds (6.5)**

6. Cloud Names, Lightning and Chemistry (6.7)

Microphysics of Ice Clouds



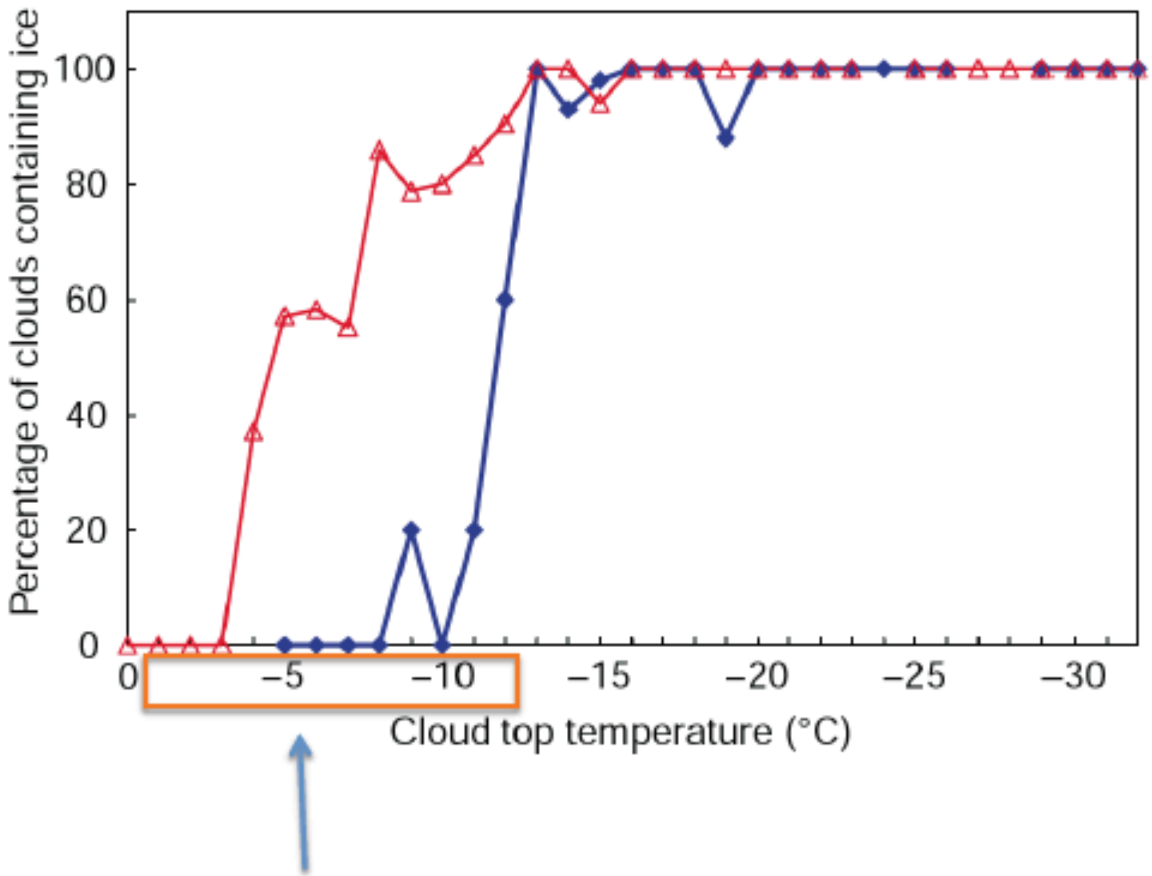


Clouds below the 0˚ isotherm are referred to as ***warm clouds***.
Clouds above are called ***cold clouds***.

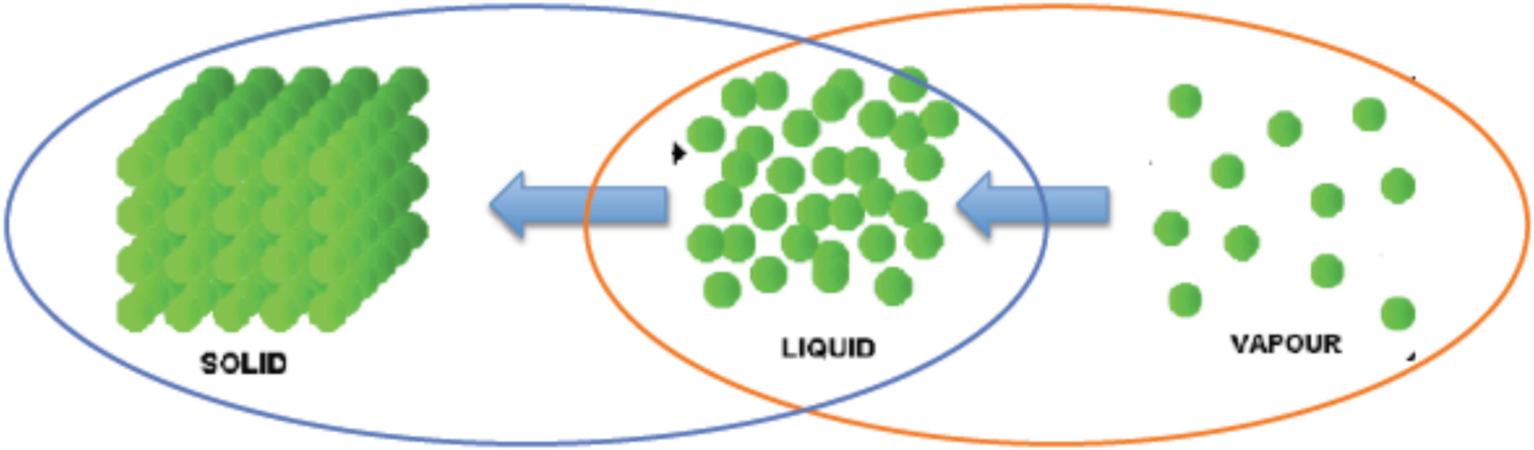
Microphysics of cold clouds are far more complicated than that of warm clouds. We still lack a unified theory to treat them.

Microphysics of Ice Clouds

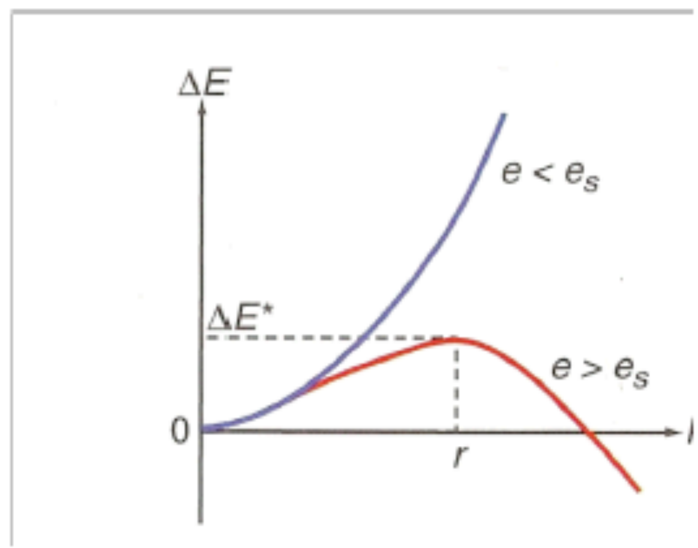
Percentage of clouds containing ice particles as a function of cloud top temperature



For this temperature range, clouds may exist only as supercooled water droplets (i.e., no ice crystals).

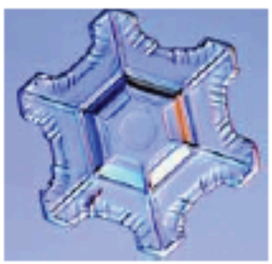


<u>Vapor-to-droplet</u>: a nucleation problem; needs a large enough nucleus to condense vapor upon (root reason: combat surface tension at liquid/vapor interface).



<u>Water droplet-to-ice particle</u>: also a nucleation problem; needs an ice embryo within a droplet that exceeds a critical size (root reason: combat surface free energy of a crystal/liquid interface).

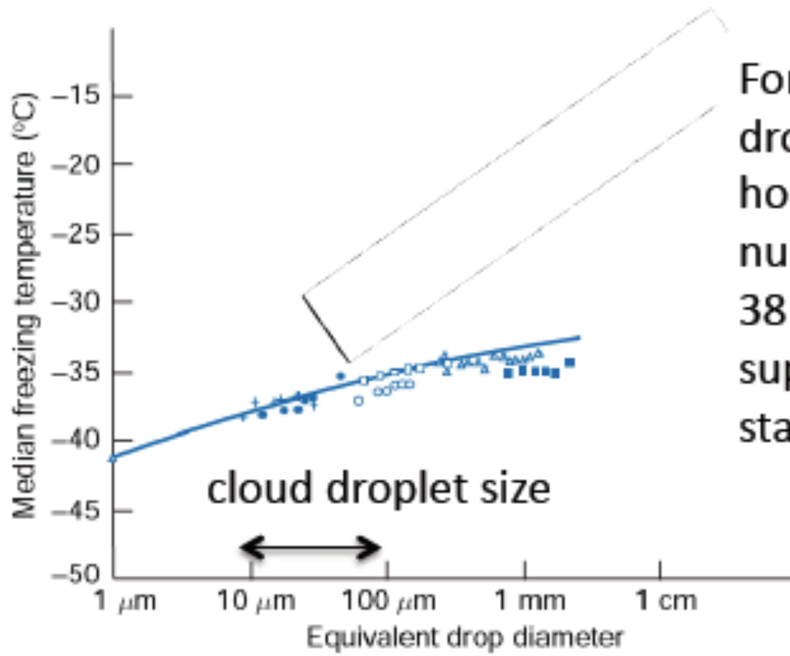
Homogeneous nucleation



The larger the droplet, the better the chance to form this critical-size nucleus (through, e.g., statistical fluctuation of molecular arrangement of water to form a small ice-like structure).

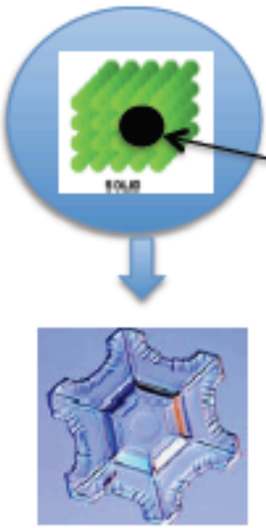
The colder the temperature, the more likely this nucleus will form.

Once this nucleus forms, the whole particle will freeze (Gibbs free energy starts to decrease spontaneously). This is why ice cubes freezes so easily – very big!

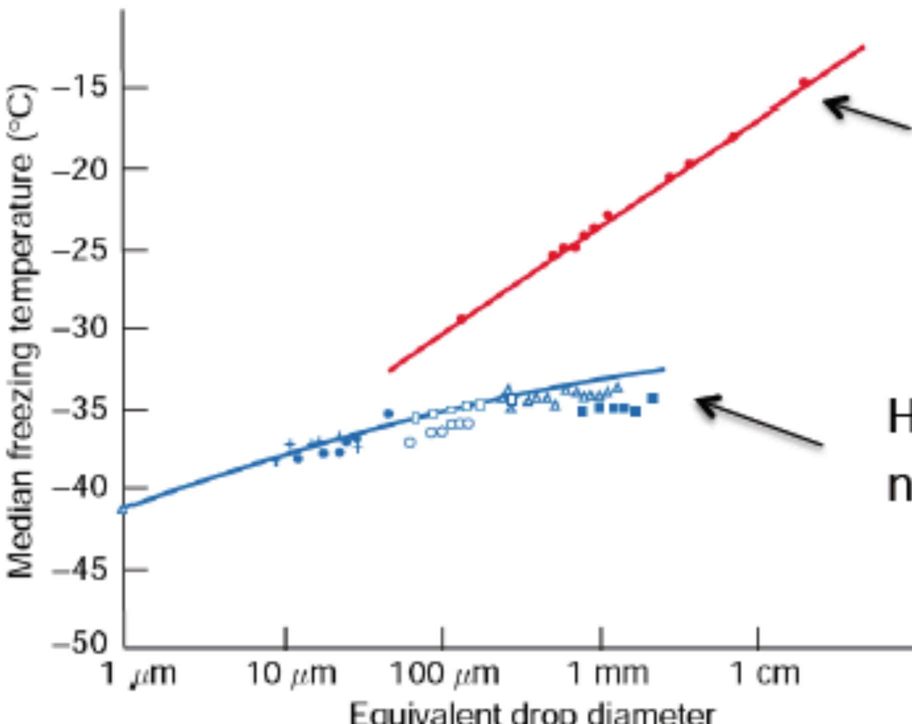


For a typical cloud droplet (~ 20 μm), homogeneous nucleation occurs at ~ -38 ^{0}C (~ 8.5 km). So, super-cooled water can stay way below 0 ^{0}C.

Heterogeneous nucleation



<u>Ice nucleus</u> (counterpart of CCN): water molecules in the droplet collect onto a foreign particle to form an ice-like structure that serves as the nucleus (after this, Gibbs free energy decreases and the whole droplet freezes)



Heterogeneous nucleation (occurring at higher temperature)

Homogeneous nucleation

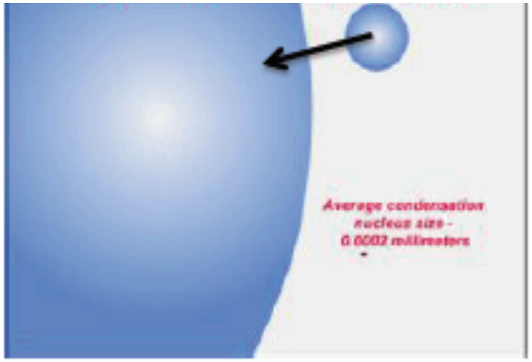
Microphysics of Ice Clouds

Typical CCN concentration (100 cm^{-3}) is 100,000 times greater than that of IN (1000 m^{-3} or 0.001 cm^{-3}). Note that 1 $m^3 = 10^6$ cm^3.

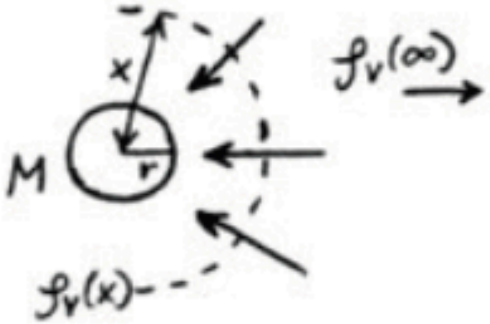
So, ***IN are scarce***. Homogeneous nucleation is rather common in ice clouds (never happens in warm clouds).

The main reason for the scarcity of IN is because ice crystals are "picky": they need the IN to have similar crystal lattice structure. Clay (Kaolinite) is a good IN. Another artificial IN is AgI (Silver Iodine).

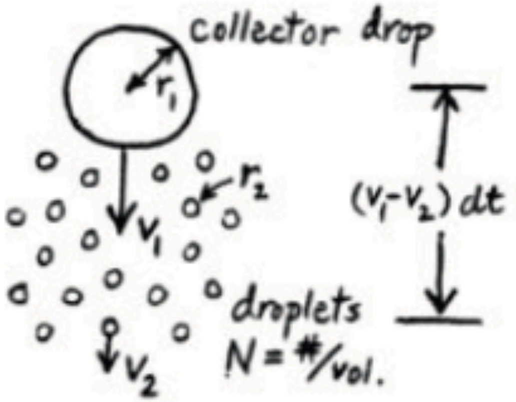
Microphysics of Ice Clouds



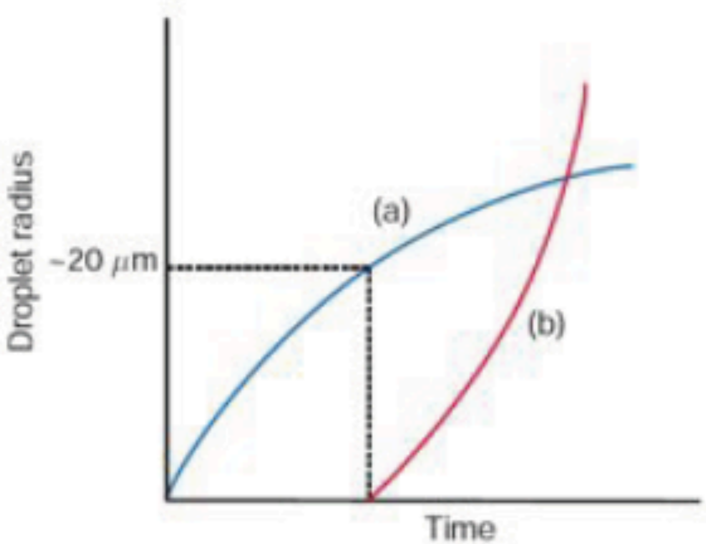
Let's review growth of water droplet and find analogy



$$\frac{dr}{dt} \approx \frac{1}{r}\frac{D\rho_v(\infty)}{\rho_l}S$$

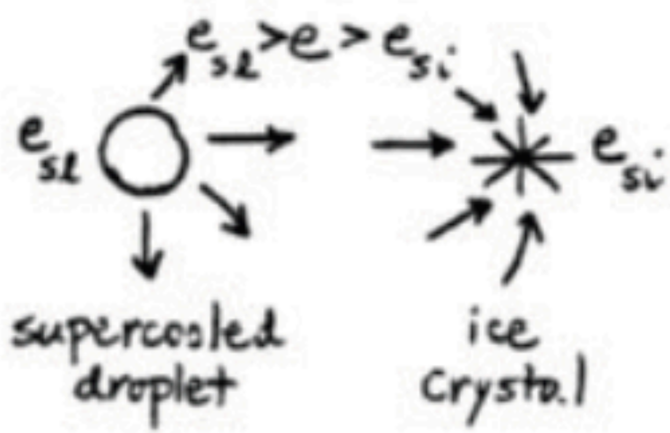


$$\frac{dr_1}{dt} = \frac{1}{18}\frac{g w_l E}{\eta} r_1^2$$



Microphysics of Ice Clouds

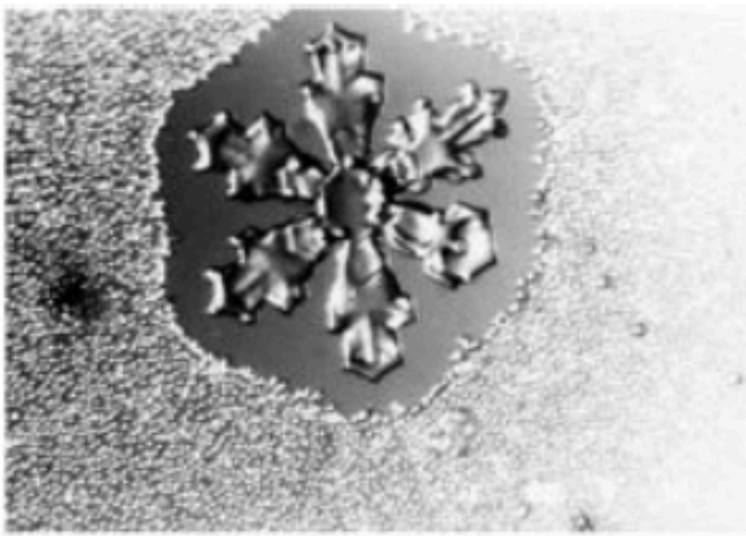
Diffusional growth of ice crystal from vapor at the expense of water droplet – a much more effective growth & faster mechanism than the water phase counterpart

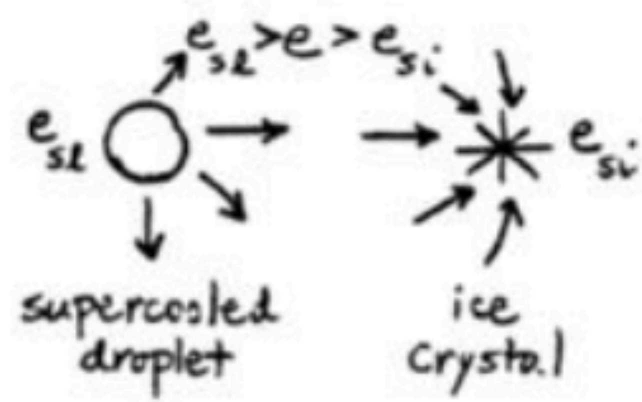


Sub-saturated w.r.t. water

Super-saturated w.r.t. ice

Laboratory demonstration of the growth of an ice crystal at the expense of surrounding super-cooled water droplets



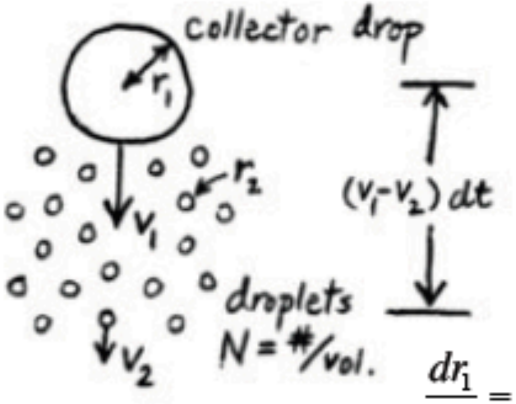


Calculations show that ice particle can from through this way to 0.5 mm or 500 µm (close to precipitation size) within 30 min. But beyond that, the growth rate will be slow.

Note that for water droplet, the diffusional growth will never pass 20 µm in a reasonable amount of time.

Growth via Collision

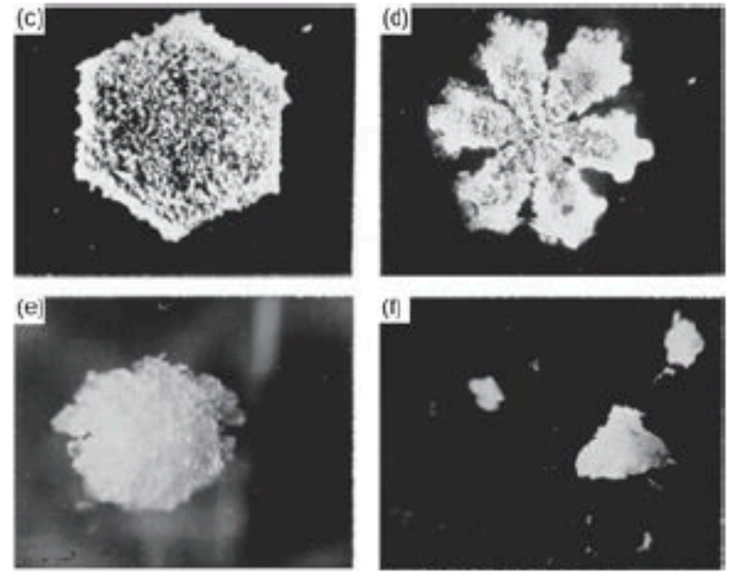
Growth of water droplets by coalescence



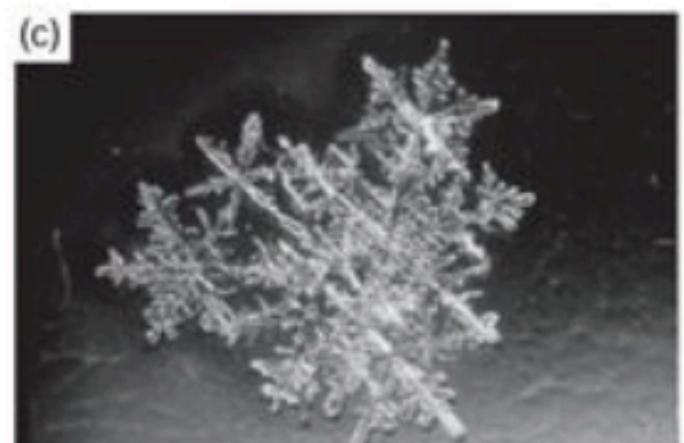
$$\frac{dr_1}{dt} = \frac{1}{18}\frac{g w_l E}{\eta} r_1^2$$

Counterpart in the ice phase

Rimming: ice particles colliding with super-cooled droplets



Aggregation: ice particles colliding with each other



WHAT ARE SUPERCOOLED DROPLETS?

- Liquid water that exists in clouds at temperatures below 0˚C

HOMOGENEOUS NUCLEATION OF ICE PARTICLES

- Change aggregation of frozen water leading to the growth of an ice cloud particle. Only water is present.

Ice nucleation processes:

<u>Condensation-Freezing</u>: 2 step process, water vapor condenses to form a liquid, then the liquid freeze.

<u>Deposition</u>: transfer of water vapor directly to ice

*We will not cover preactivation in this class. Skip figure 6.30.

Saturation with respect to liquid vs ice

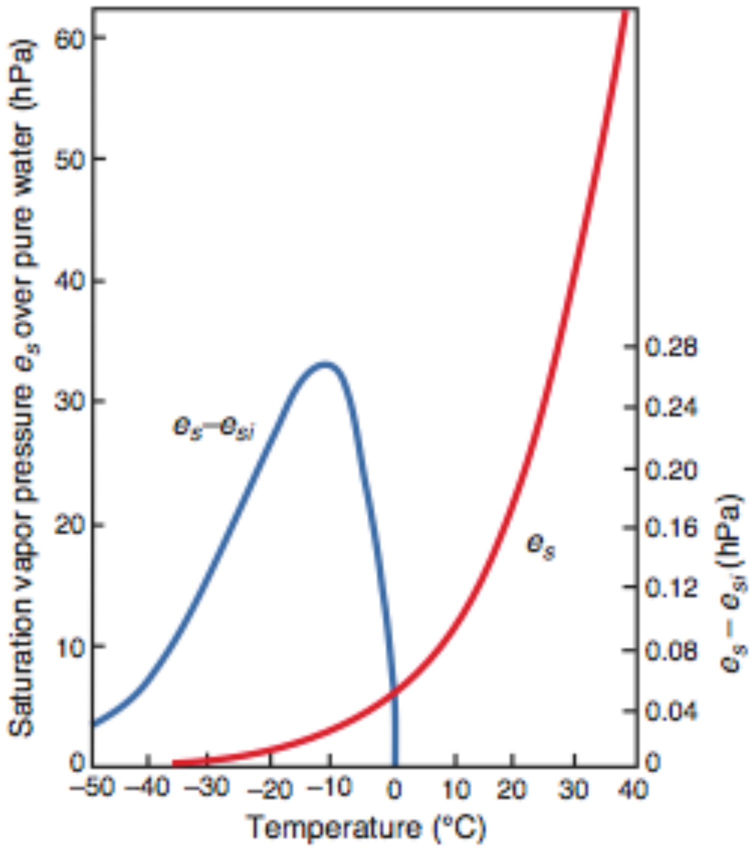


Fig. 3.9 Variations with temperature of the saturation (i.e., equilibrium) vapor pressure e_s over a plane surface of pure water (red line, scale at left) and the difference between e_s and the saturation vapor pressure over a plane surface of ice e_{si} (blue line, scale at right).

Focus on Blue Curve.

Use y-axis on the right hand side.

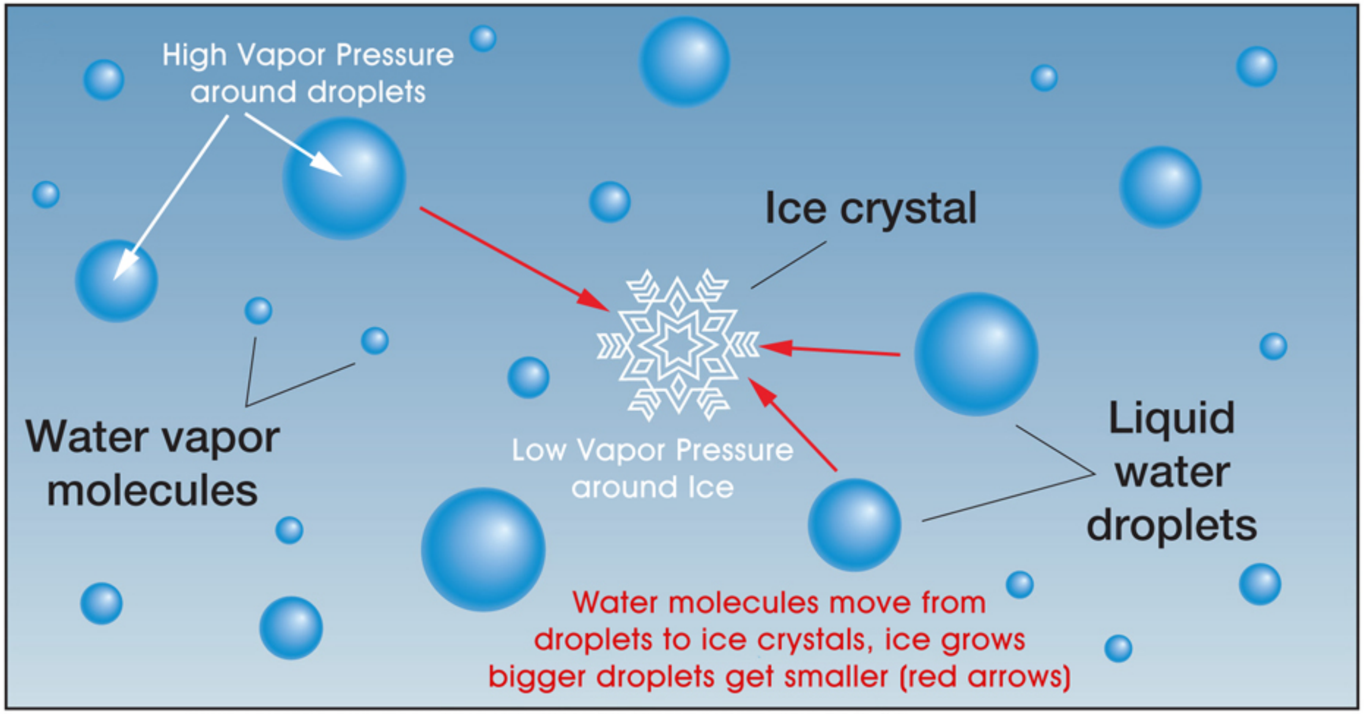
Take home message:

$$e_s > e_{si}$$

Section 6.5.4: Formation of precipitation in cold clouds

Cold-rain process (Wegener-Bergeron-Findeisen Process

Supercooled vapor droplets accumulate on an ice particle through deposition opposite of sublimation.



subsaturated environment for liquid water but a supersaturated environment for ice.

Alternate to depositional growth?

Riming and aggregation (growth rate increases with size)

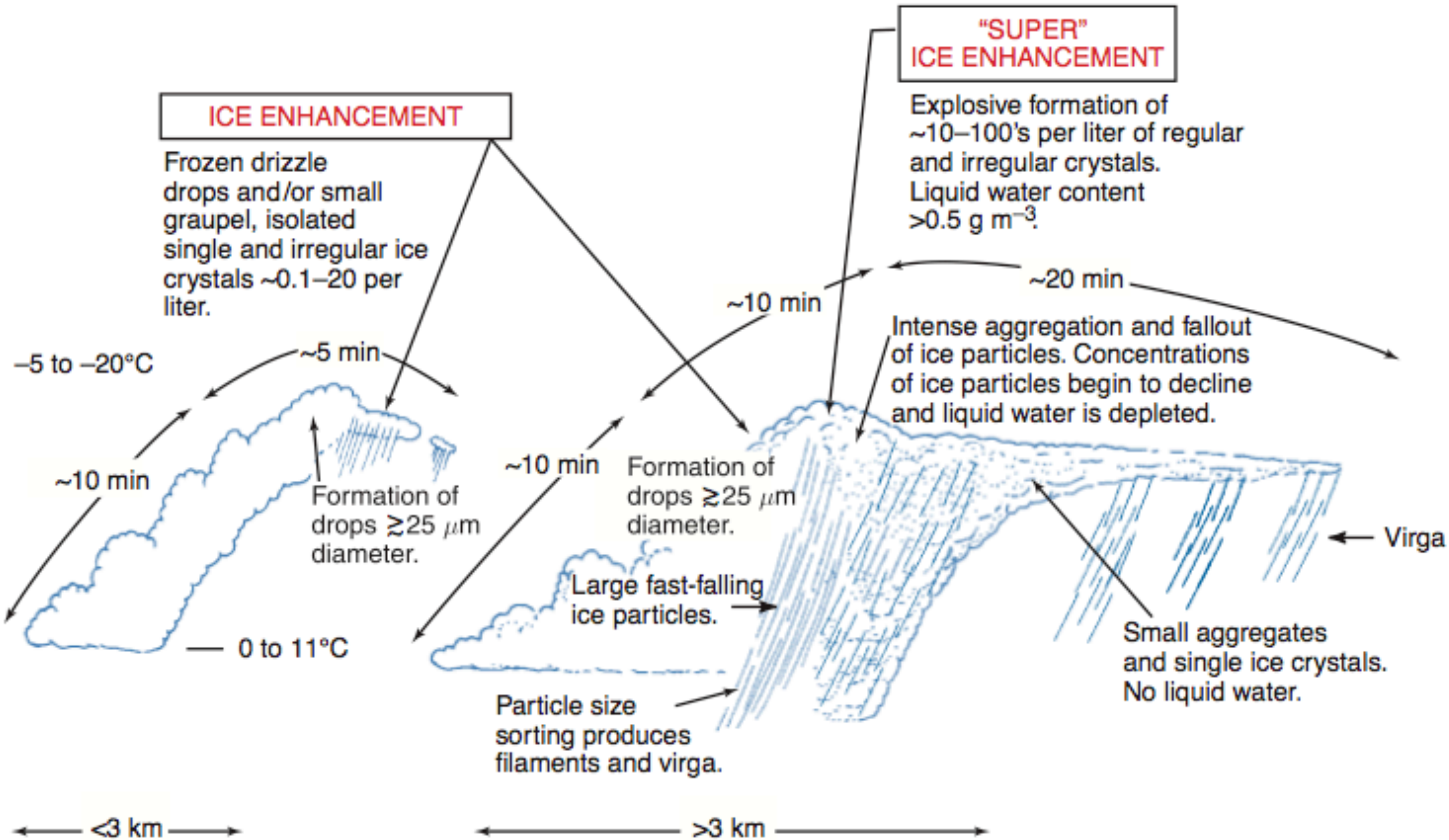


Fig. 6.35 Schematic of ice development in small cumuliform clouds. [Adapted from *Quart. J. Roy. Meteor. Soc.* **117**, 231 (1991). Reproduced by permission of The Royal Meteorological Society.]

RADAR ECHO TO MEASURE CLOUD MICROPHYSICS

Large ice particles grow, fall, and melt to form rain.

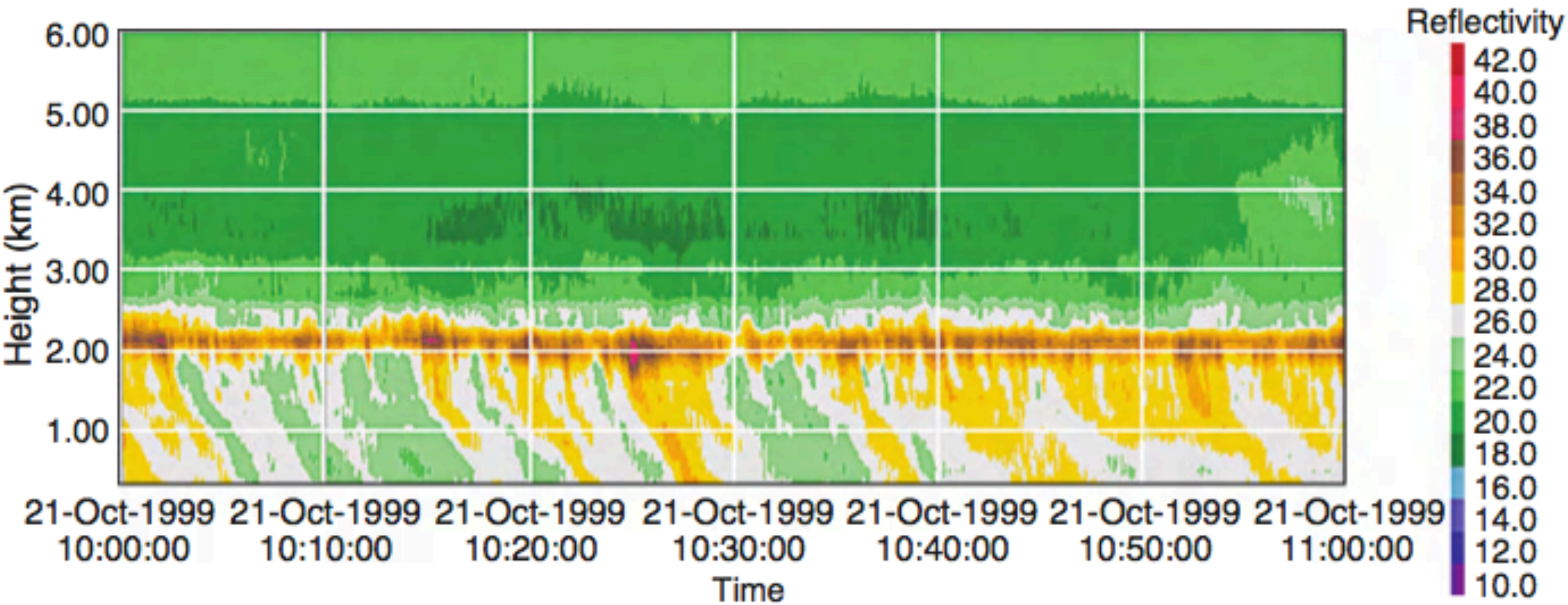


Fig. 6.45 Reflectivity (or "echo") from a vertically pointing radar. The horizontal band of high reflectivity values (in brown), located just above a height of 2 km, is the melting band. The curved trails of relatively high reflectivity (in yellow) emanating from the bright band are *fallstreaks* of precipitation, some of which reach the ground. [Courtesy of Sandra E. Yuter.]