Microphysics of Cold Clouds

- *Cold clouds* extend above 0 °C.
- Liquid droplets below 0 °C are *supercooled.*
- A *mixed-phase cloud* contains both ice particles and supercooled droplets.
- A *glaciated* cloud contains only 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

METEOROLOGY

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)

METEOROLOGY

Nucleation of Ice Particles

- **Freezing of a supercooled droplet**
  - *Homogeneous nucleation*
    - No foreign particles
    - Occurs between -35°C and -41°C
  - *Heterogeneous nucleation*
    - Droplet contains a *freezing nucleus*
    - Freezing temperature increases with droplet size

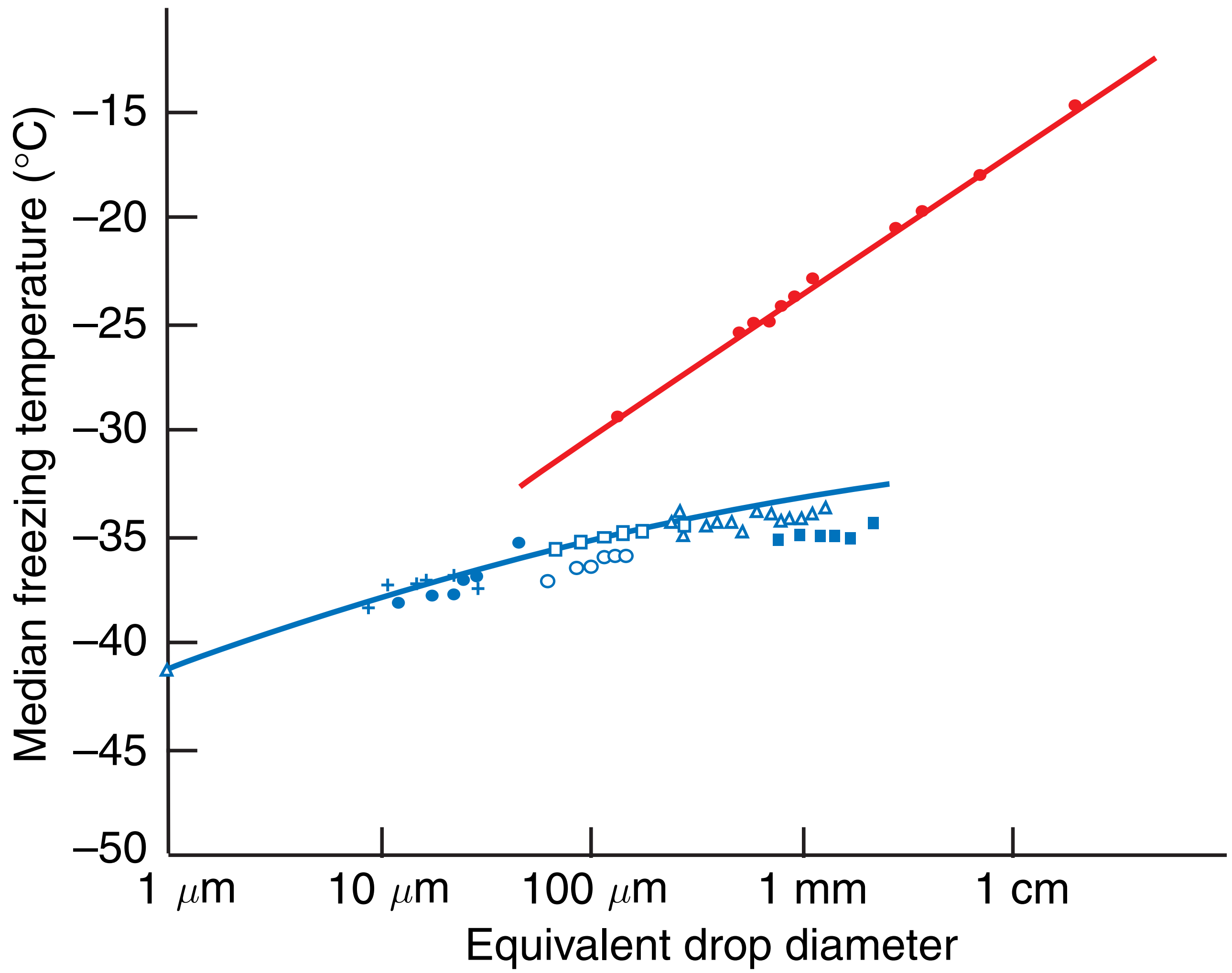
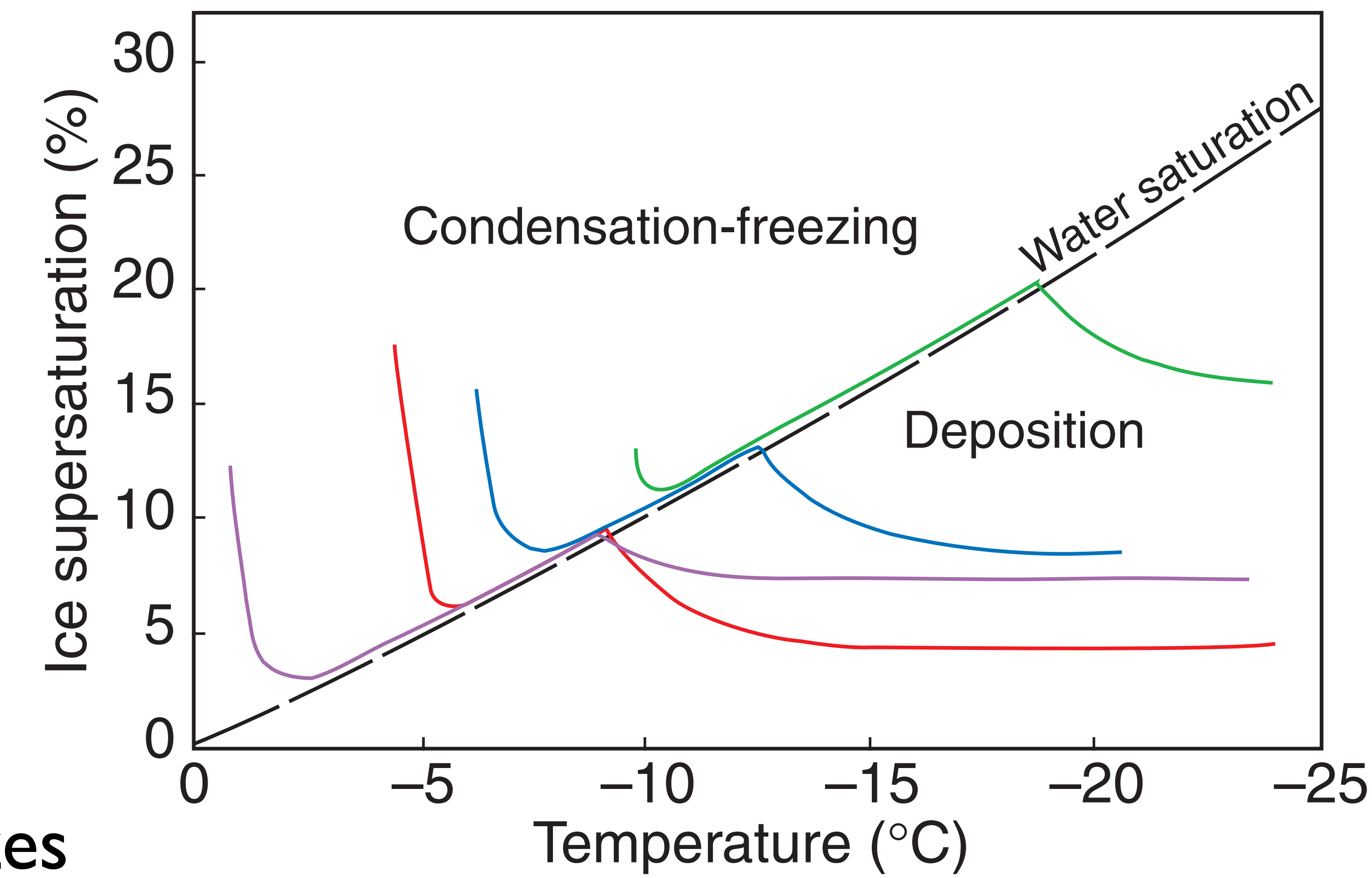


Fig. 6.29 Median freezing temperatures of water samples as a function of their equivalent drop diameter. The different symbols are results from different workers. The red symbols and red line represent heterogeneous freezing, and the blue symbols and line represent homogeneous freezing. [Adapted from B. J. Mason, *The Physics of Clouds*, Oxford Univ. Press, Oxford, 1971, p. 160. By permission of Oxford University Press.]

Nucleation of Ice Particles

- **Deposition of vapor requires**
  - supersaturation
  - temperature < 0°C
  - *deposition nuclei*
    - <u>water supersaturated:</u> vapor condenses onto *freezing nuclei* then freezes
    - <u>water subsaturated:</u> vapor deposits onto *deposition nuclei* as ice



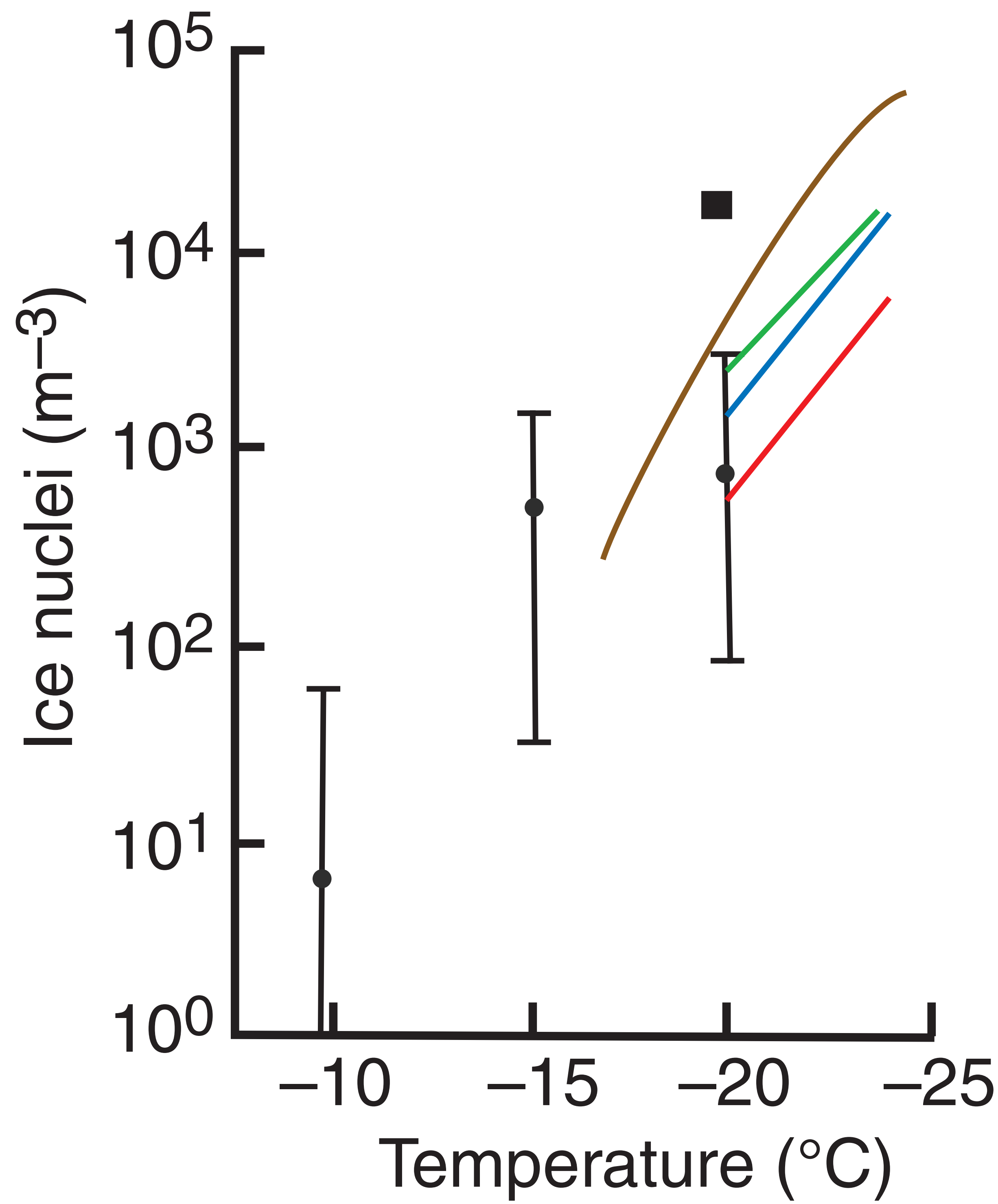
silver iodide
lead iodide
methaldehyde
kaolinite

Nucleation of Ice Particles

- Ice nuclei concentrations (N) versus temperature (T):

$$\ln N = a(T_1 - T)$$

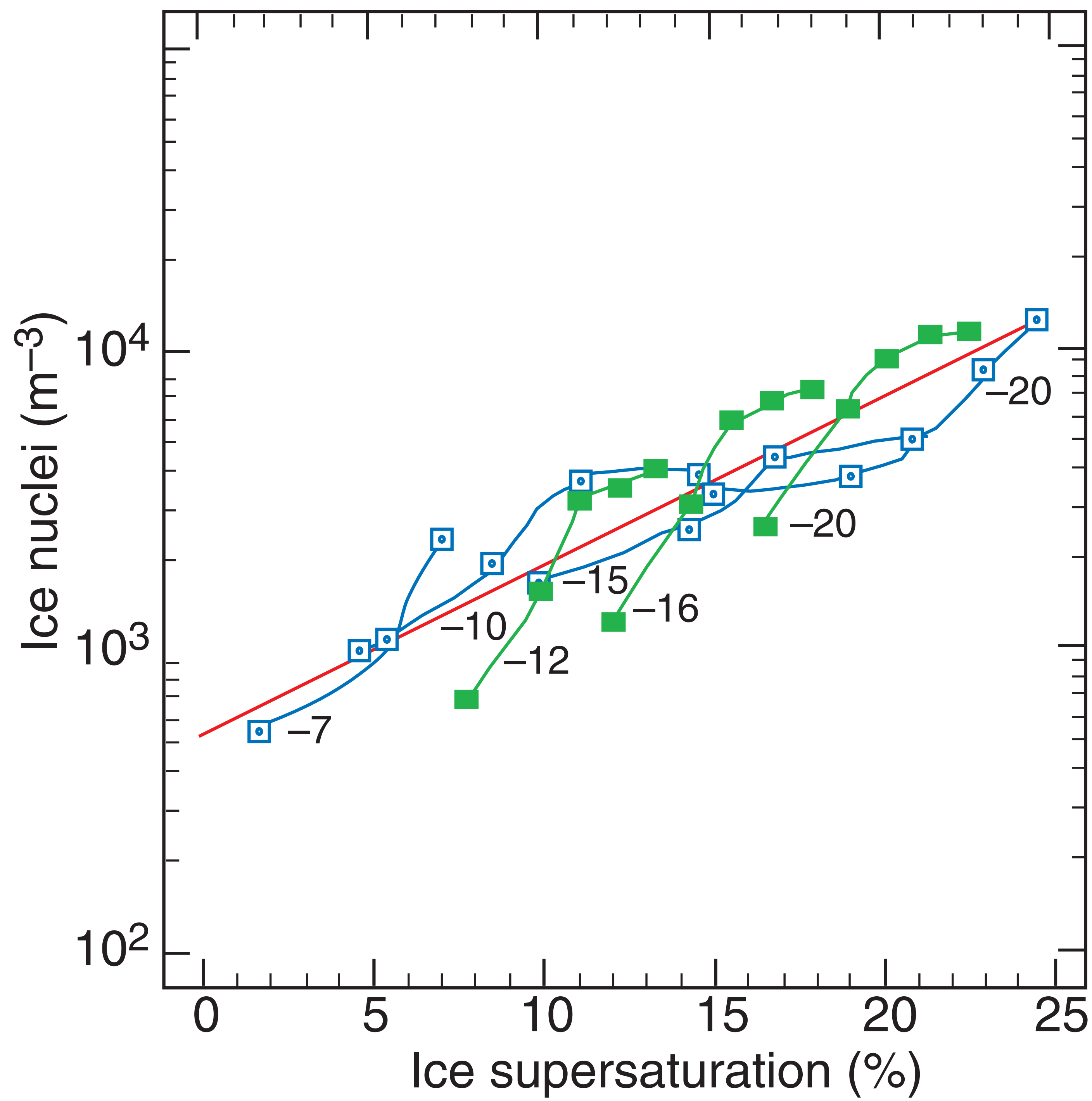
- It follows that the median freezing temperature of a droplet population should vary with diameter as shown in a previous figure.



Nucleation of Ice Particles

- Ice nuclei concentrations (N) versus ice supersaturation (S_i):

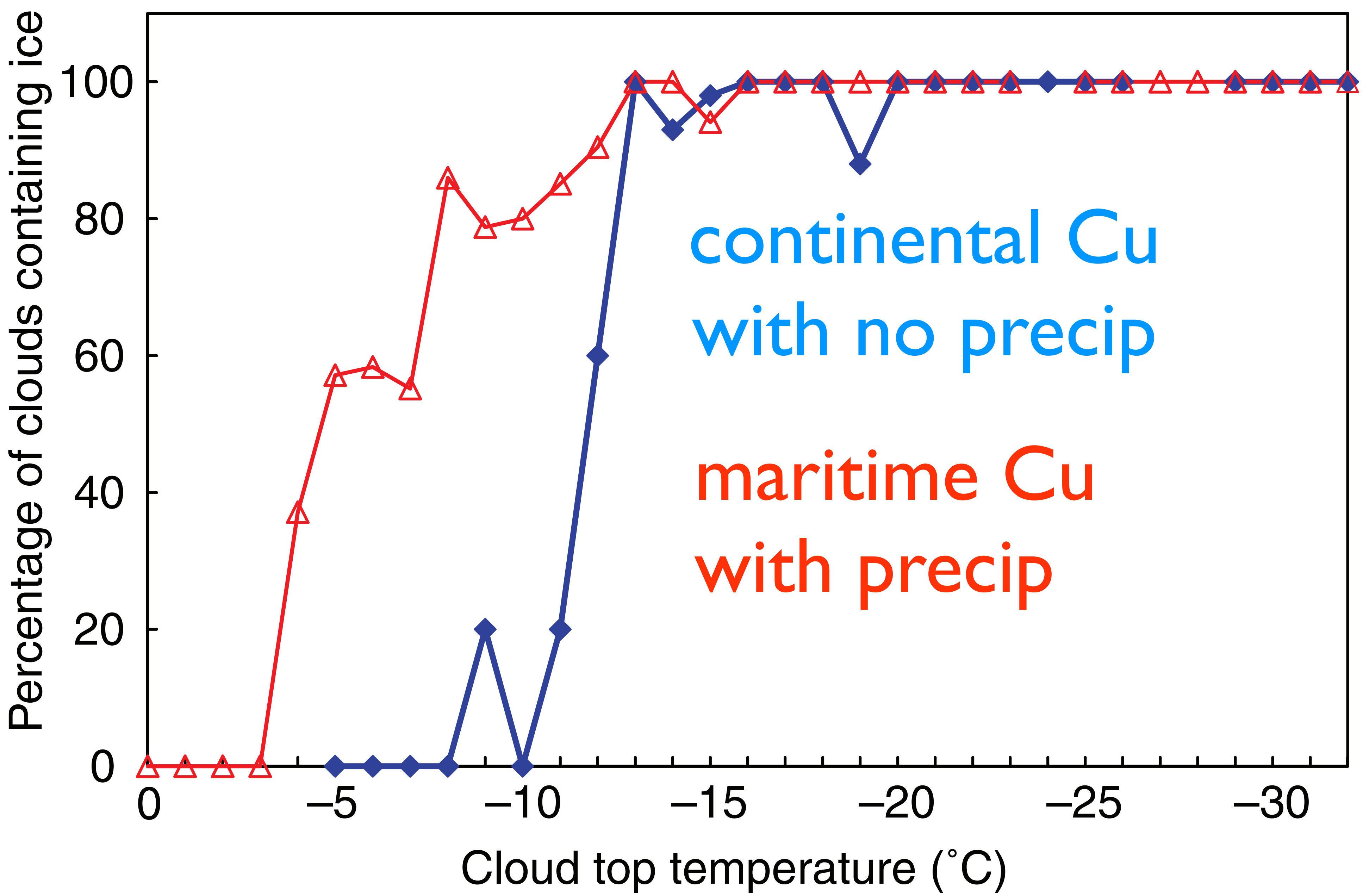
$$\ln N = a + b[100(S_i - 1)]$$



Temperatures are noted alongside each line.

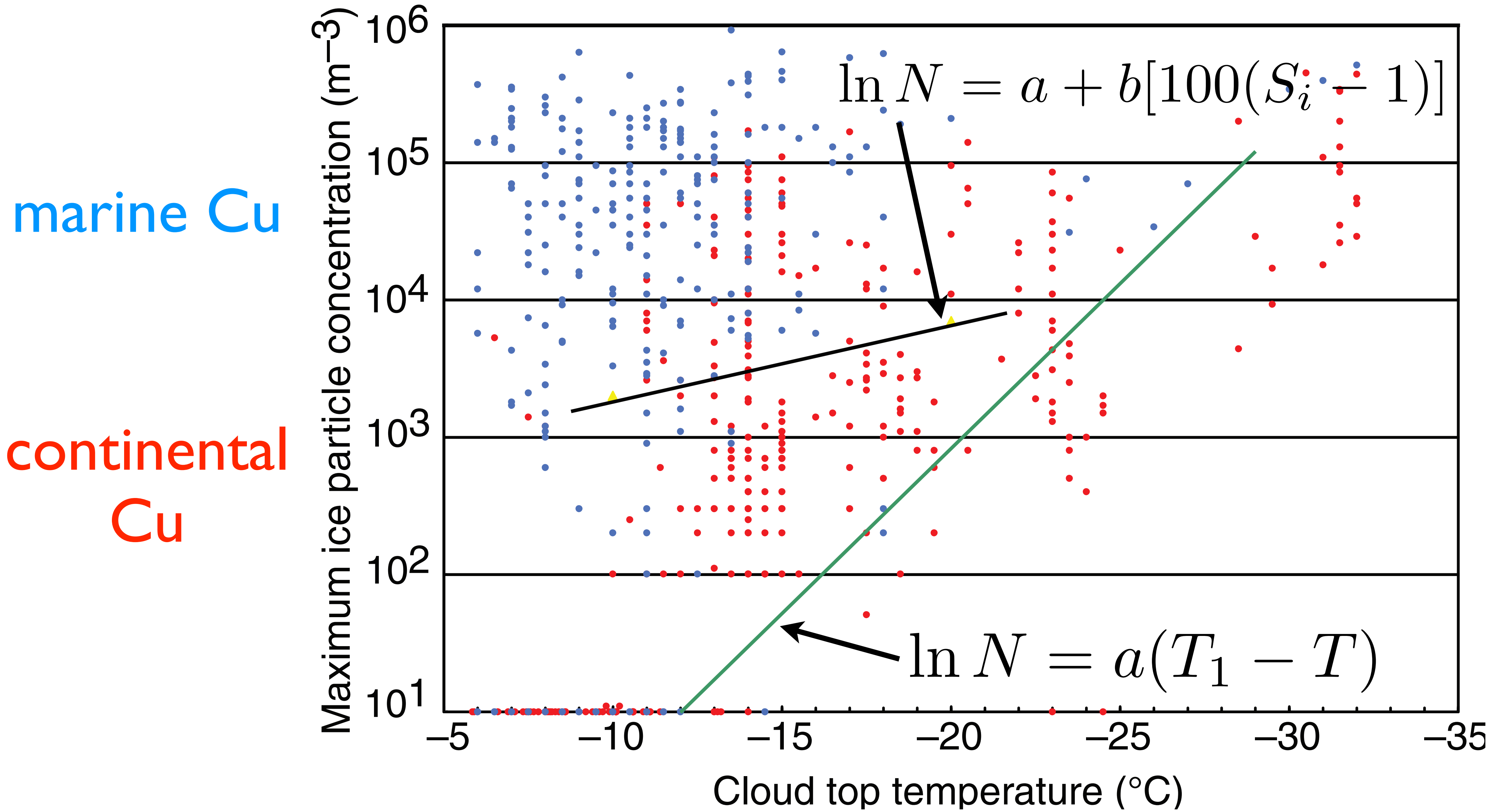
Concentrations of Ice Particles

- Ice particles occur more frequently as T decreases below 0°C.



Concentrations of Ice Particles

- Ice multiplication processes can produce many ice particles per ice nucleus.



Concentrations of Ice Particles

Ice development in small cumulus clouds

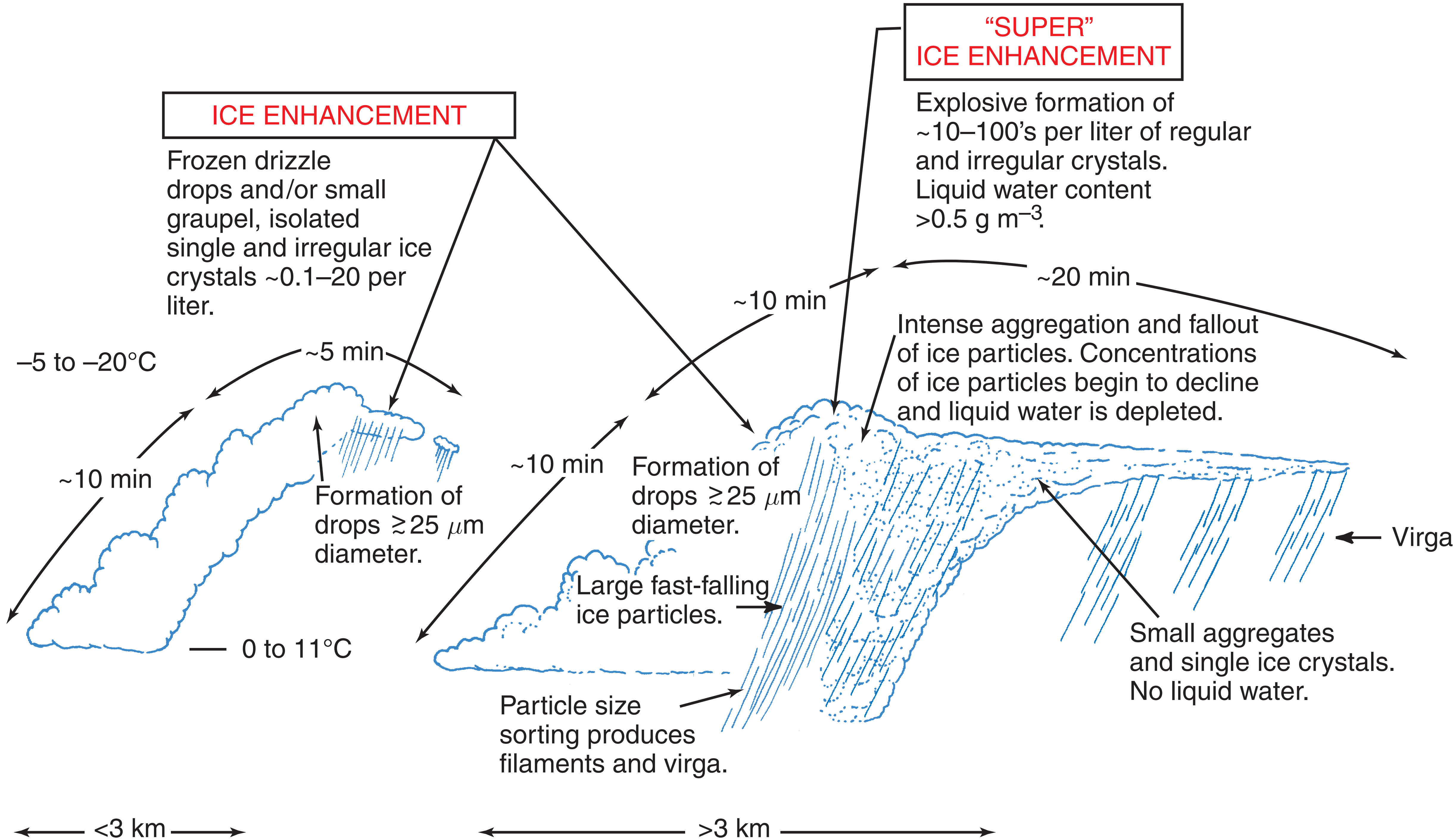


Fig. 6.35 Schematic of ice development in small cumuliform clouds. [Adapted from *Quart. J. Roy. Meteor. Soc.* **117**, 231 (1991). Reproduced by permission of The Royal Meteorological Society.]

Growth of Ice Particles in Clouds

- Growth from the vapor phase by *deposition*:
  ice crystals and snowflakes

- Growth by *riming (accretion* and *freezing* of
  supercooled cloud droplets):
  graupel and hail

- Growth by *aggregation*:
  snowflakes

Growth of Ice Particles in Clouds

Growth from the vapor phase:

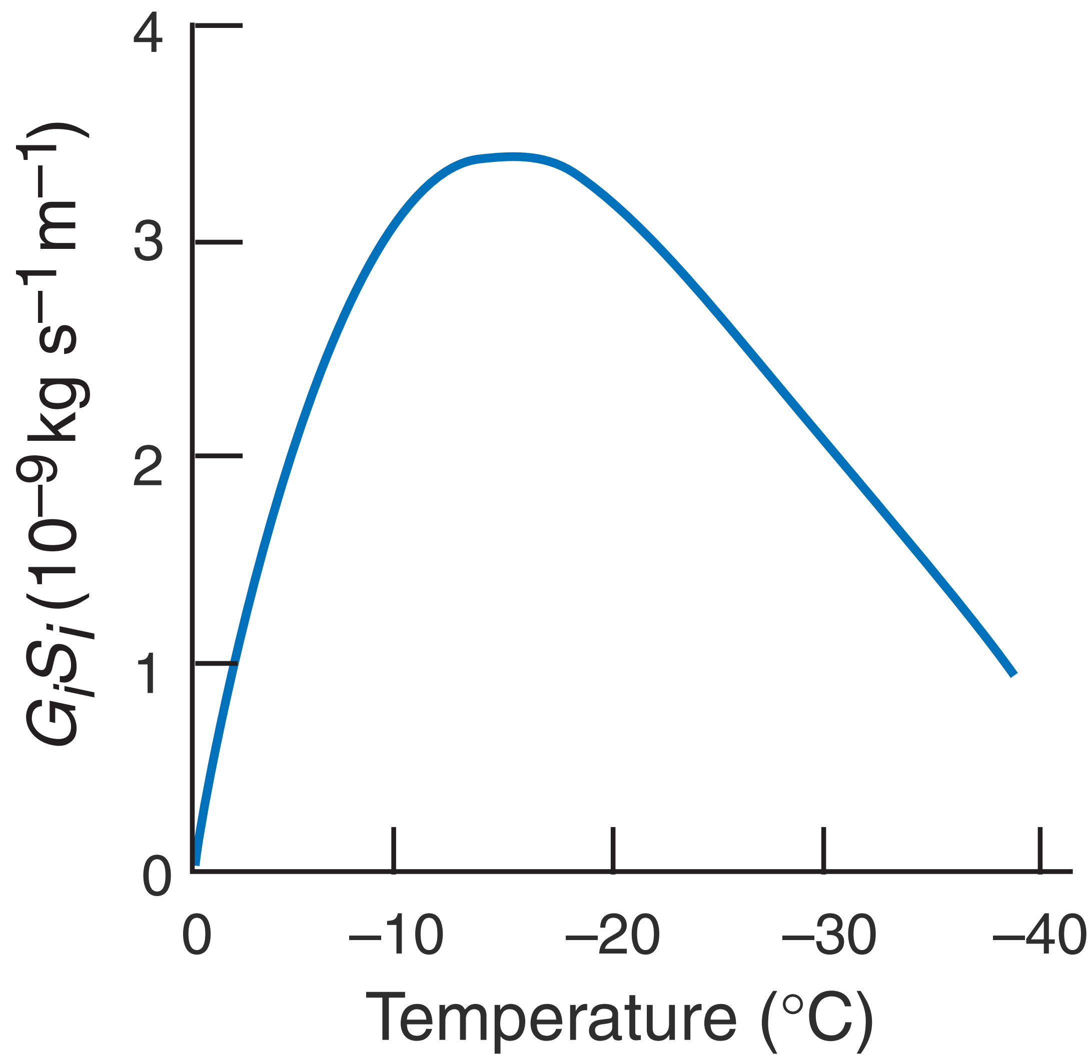
$$\frac{dM}{dt} = \frac{C}{\epsilon_0} G_i S_i$$

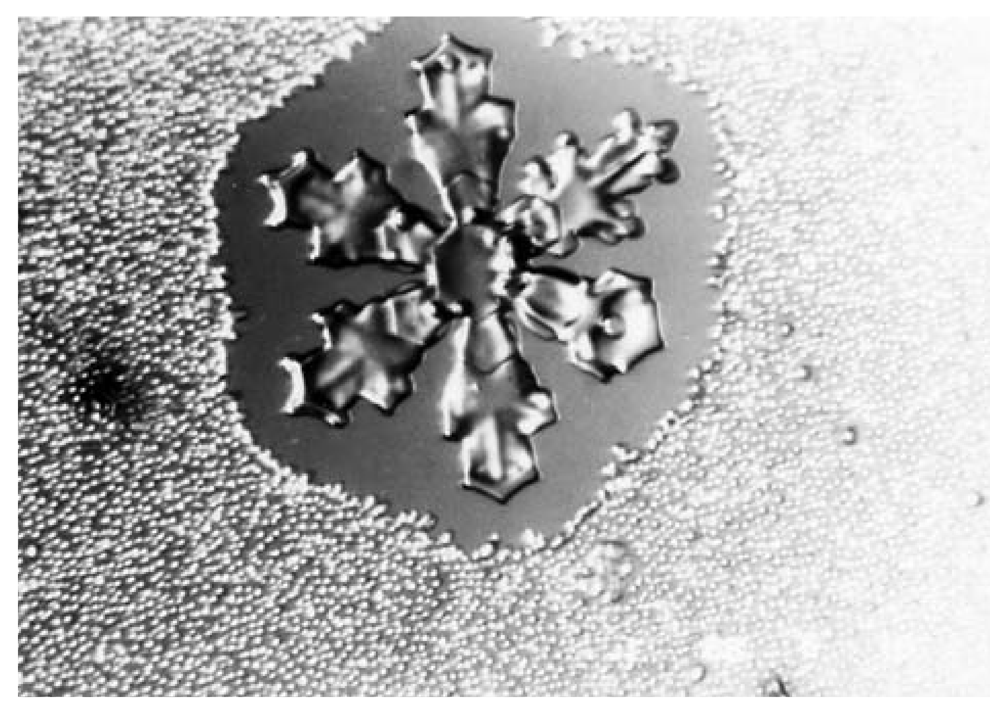
where S_i is supersaturation with respect to ice:

$$S_i = \frac{e(\infty) - e_{si}}{e_{si}},$$

and

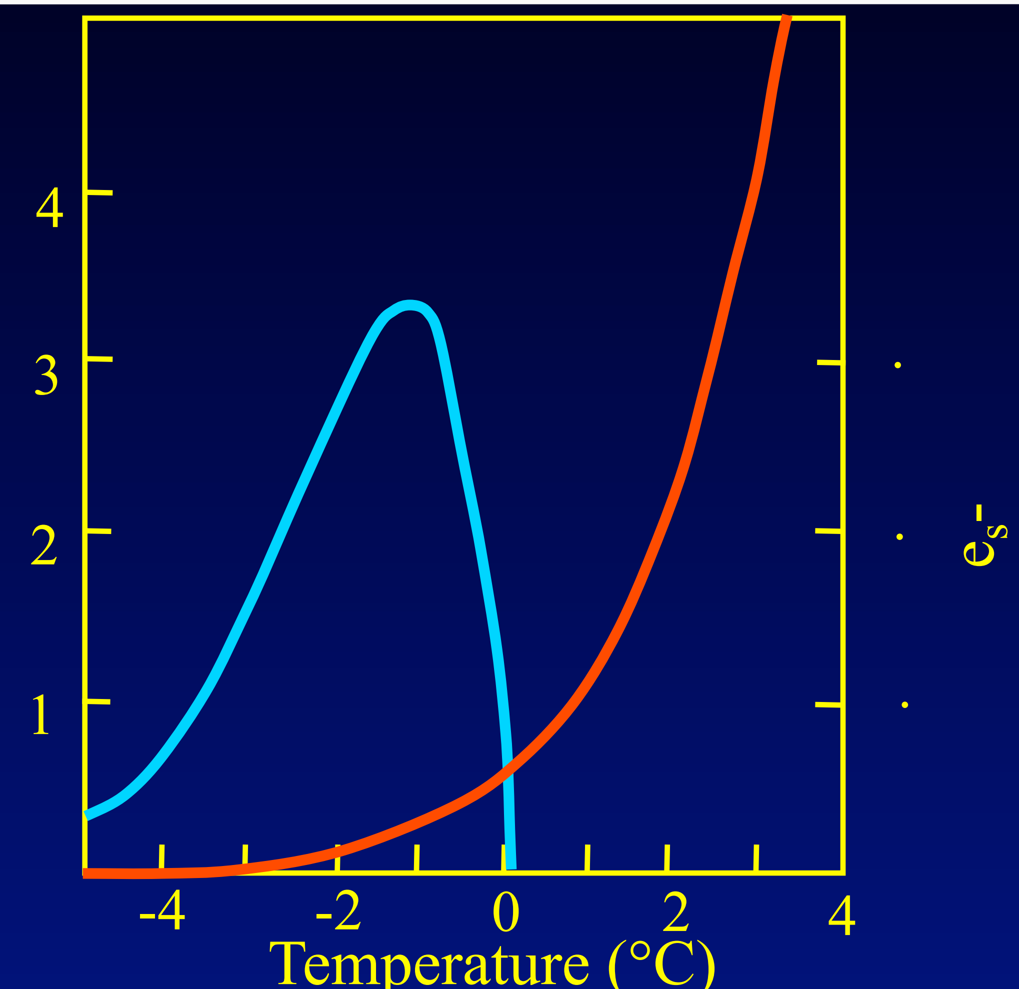
$$G_i = D\rho_v(\infty).$$

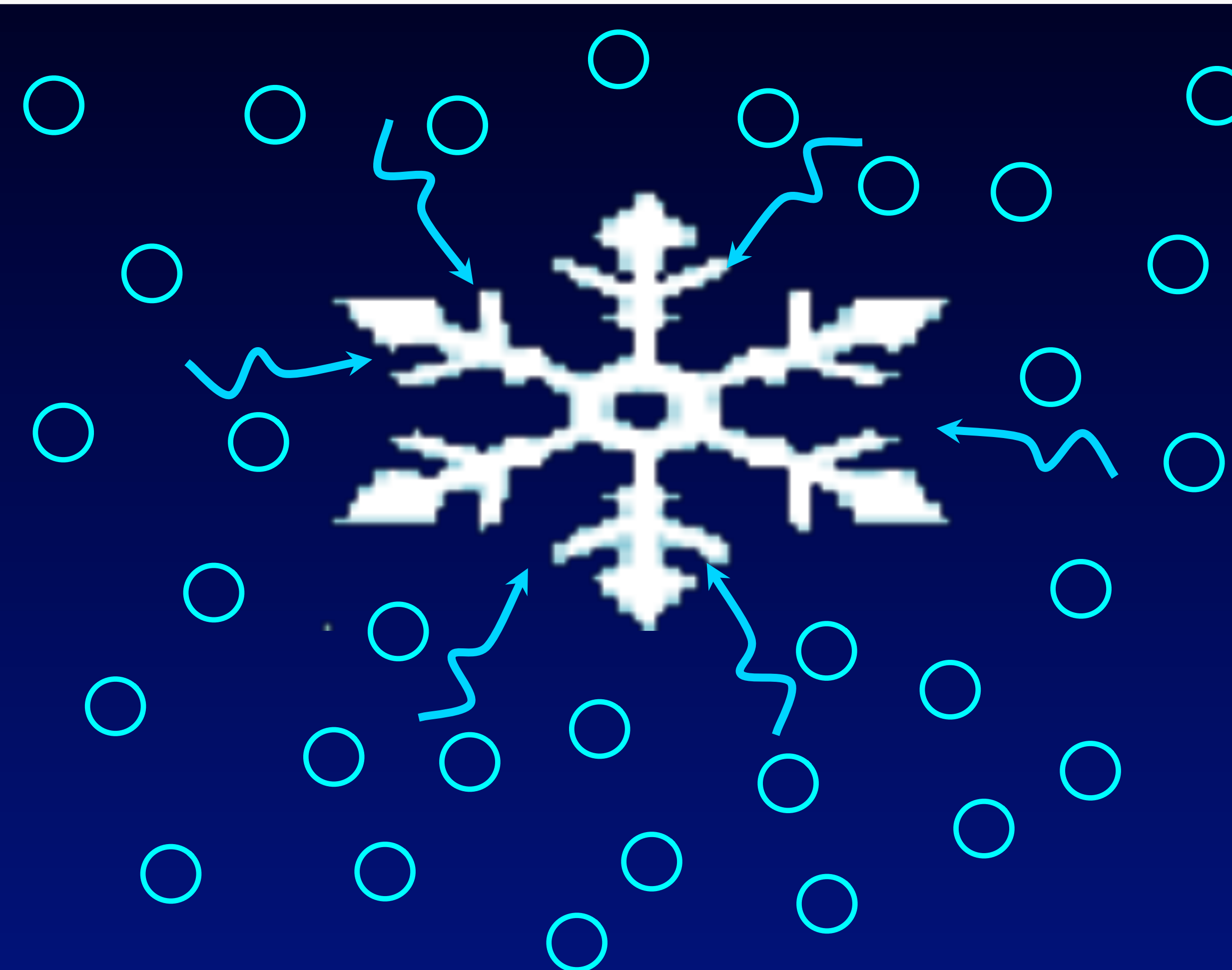




Growth of an ice crystal and evaporation of nearby supercooled droplets.

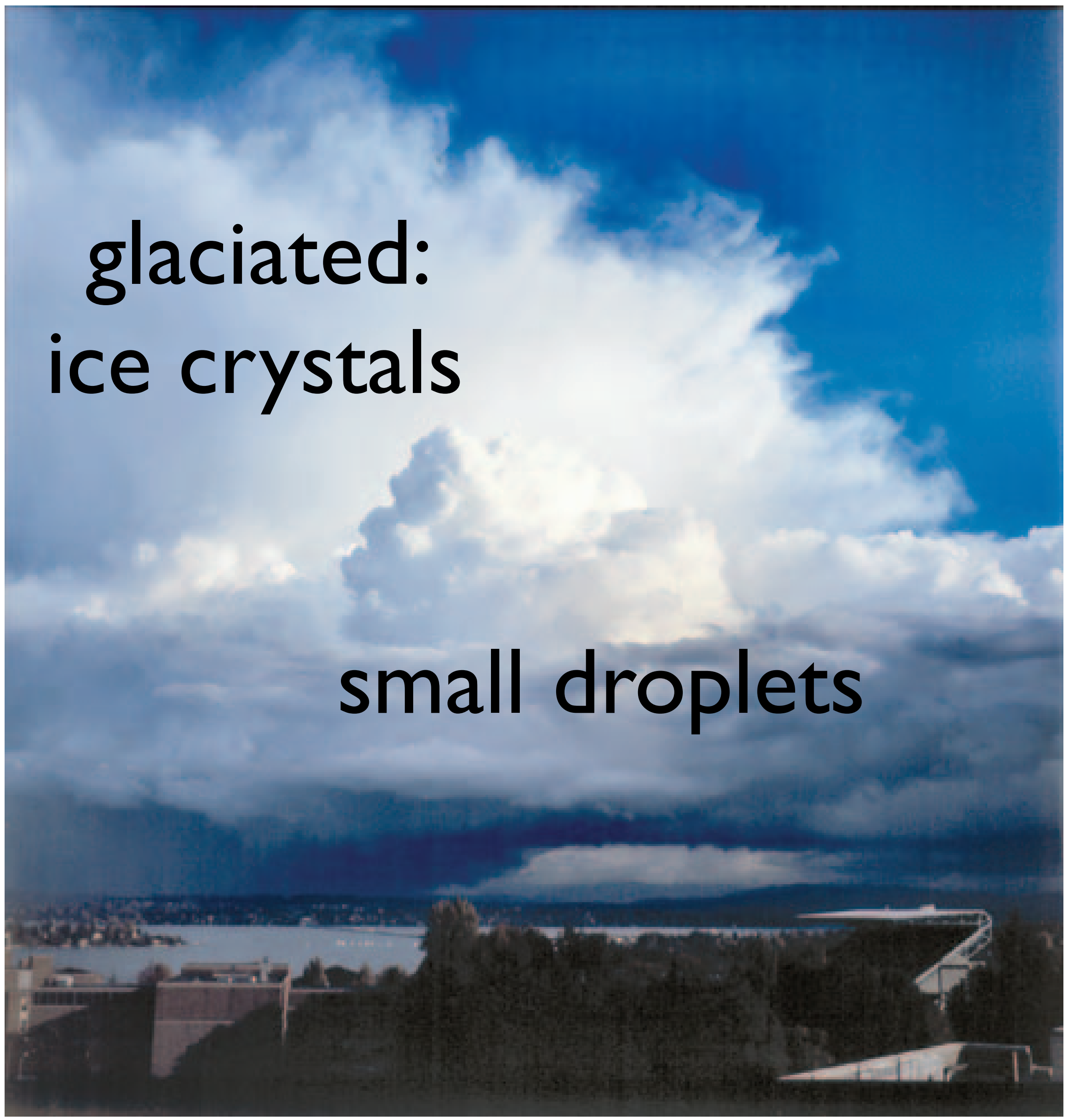
Vapor deposition (Bergeron-Findeisen Process)





- 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

Growth of Ice Particles in Clouds

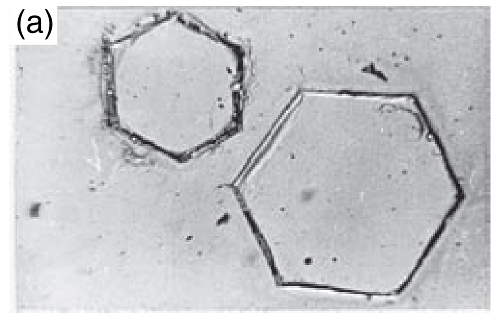


Glaciation

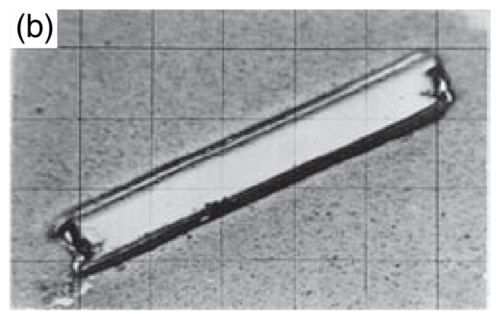
- Glaciation – Conversion from liquid to mixed-phase (water and ice) cloud
  - Gotta happen for snow

- But! Water doesn't freeze at 32°F/0°C
  - Supercooled cloud droplets – exist at temperatures below 0°C
  - They need an ice nucleus to freeze
  - Number of ice nuclei is low when you are just below freezing
  - Clouds with "warm" cloud tops
    - May have a difficult time glaciating
    - May rime instead of snow
  - Need cold cloud tops, or "ice multiplication" for cloud to glaciate

Growth of Ice Particles in Clouds

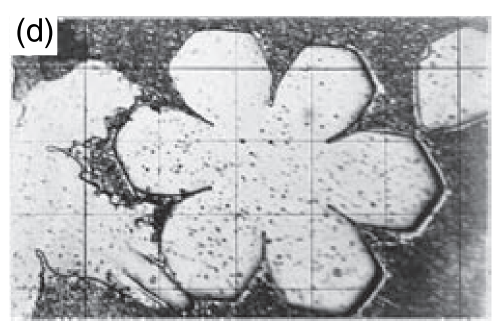


hexagonal plates

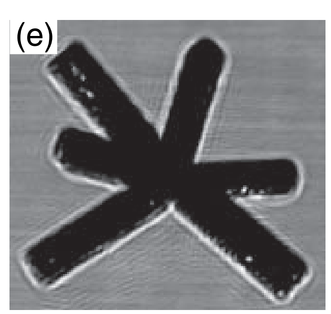


column

dendrite

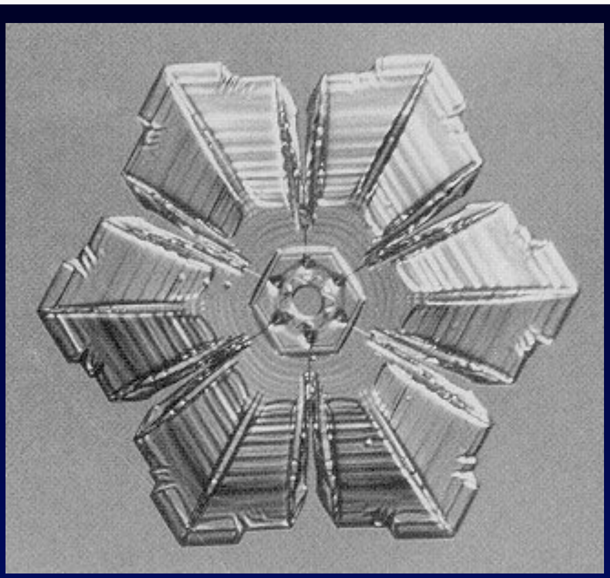


sector plate

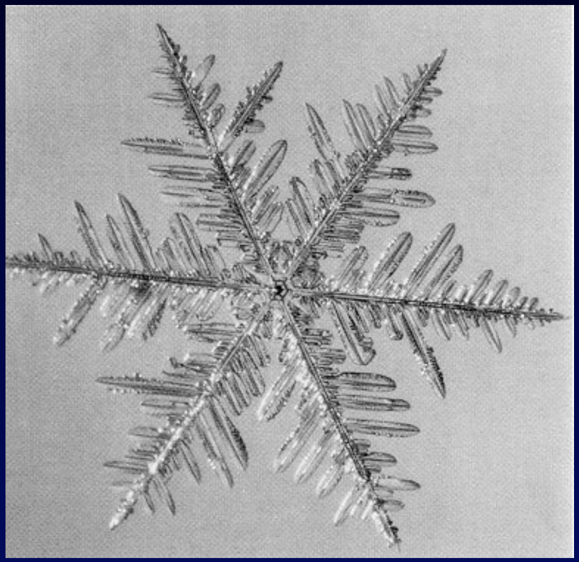


bullet rosette

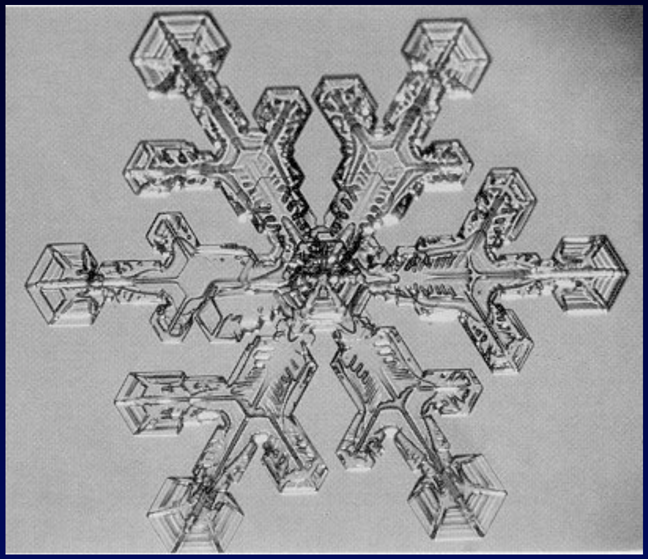
Vapor deposition (Bergeron-Findeisen Process)



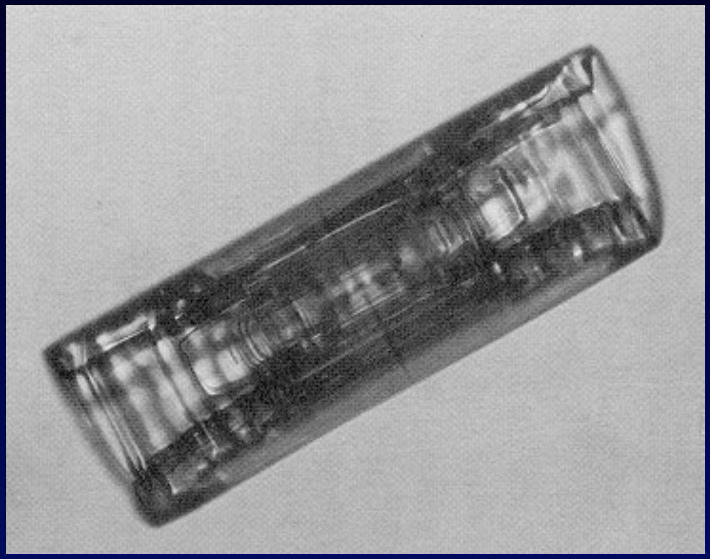
Sector plate



Stellar dendrite



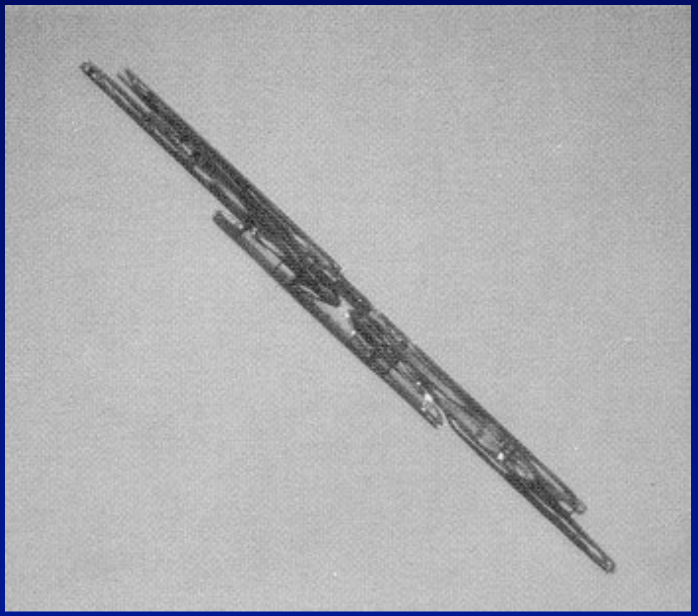
Dendritic sector plate



Hollow column

Snowcrystals.net

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



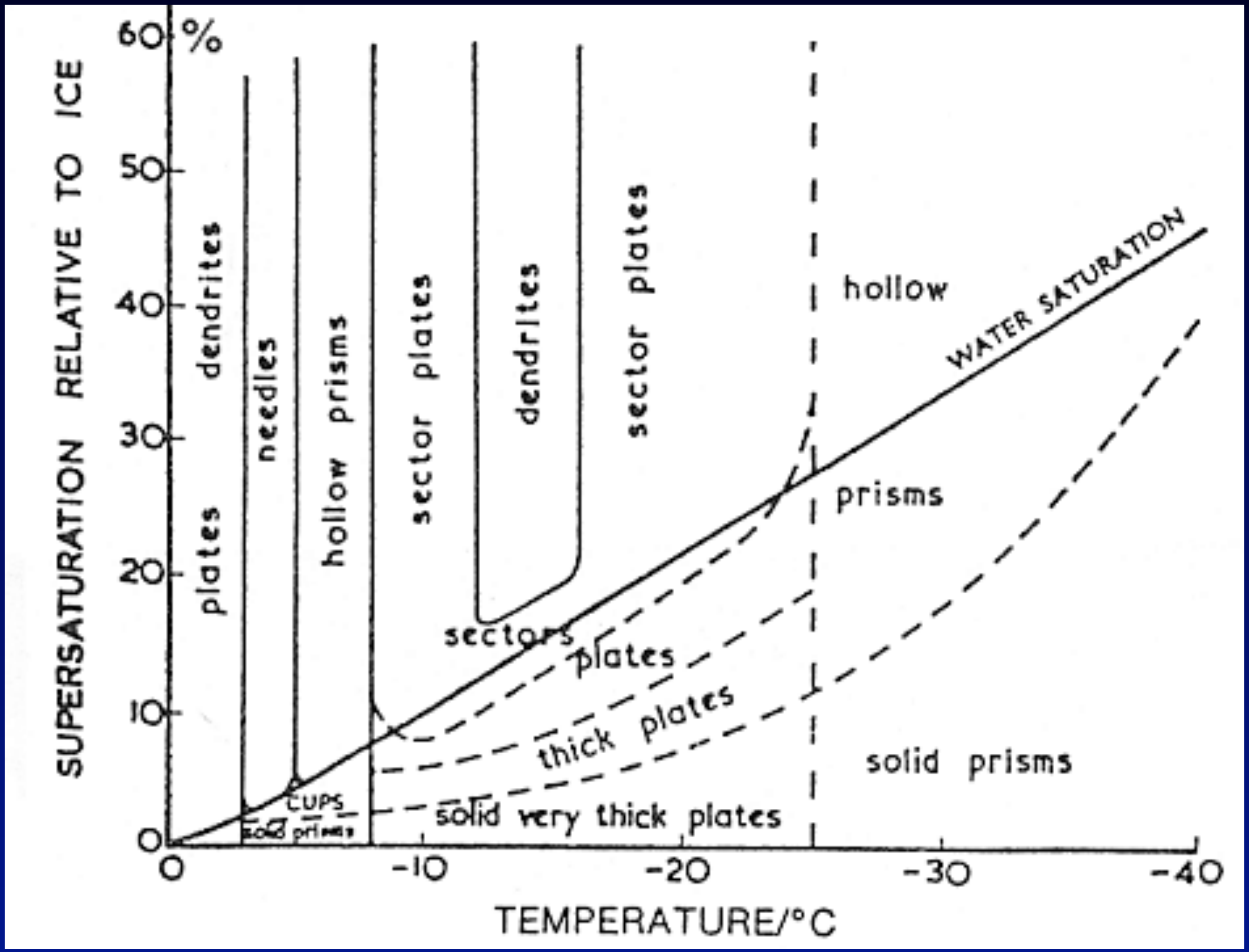
Needle

Growth of Ice Particles in Clouds

- Basic habit of an ice crystal is determined by the temperature at which it grows

Temperature (°C)	Basic habit
0 to -2.5	Plate-like
-3	Transition
-3.5 to -7.5	Column-like
-8.5	Transition
-9 to -40	Plate-like
-40 to -60	Column-like

Vapor deposition (Bergeron-Findeisen Process)



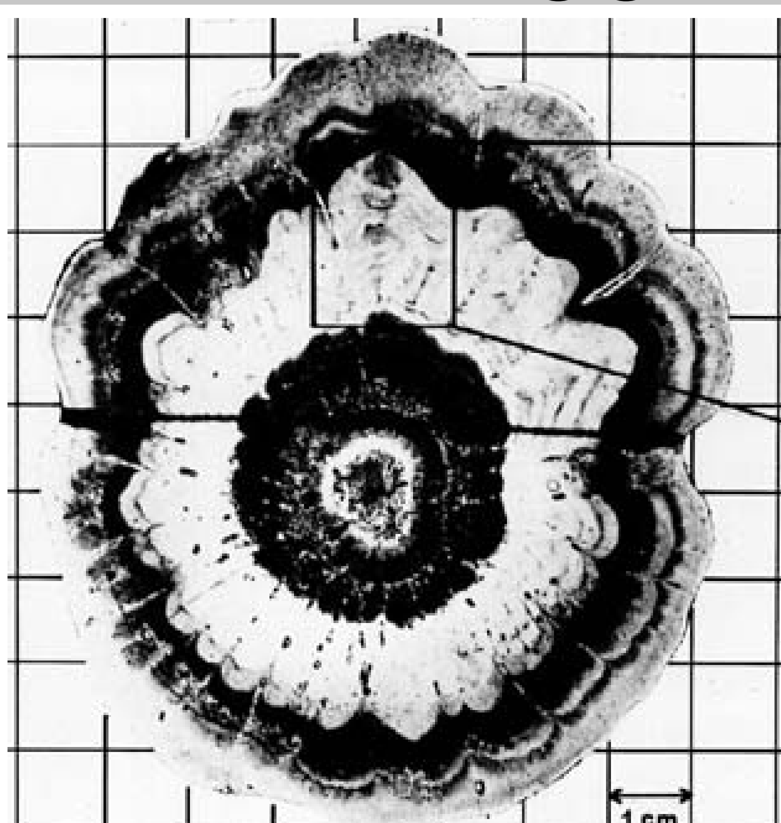
Snowcrystals.net

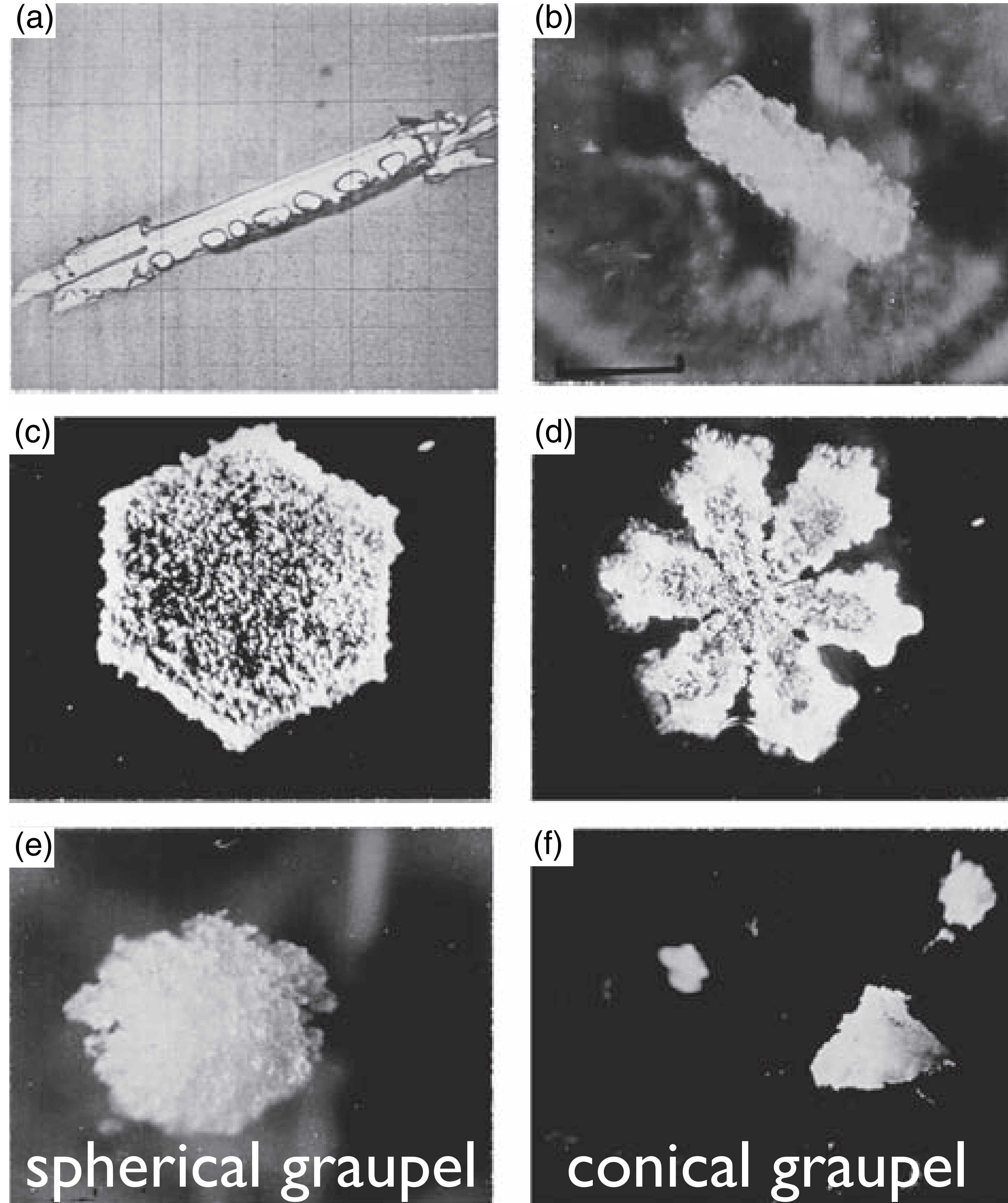
- Habit type is a function of
  - Temperature
  - Supersaturation relative to ice

Growth of Ice Particles in Clouds

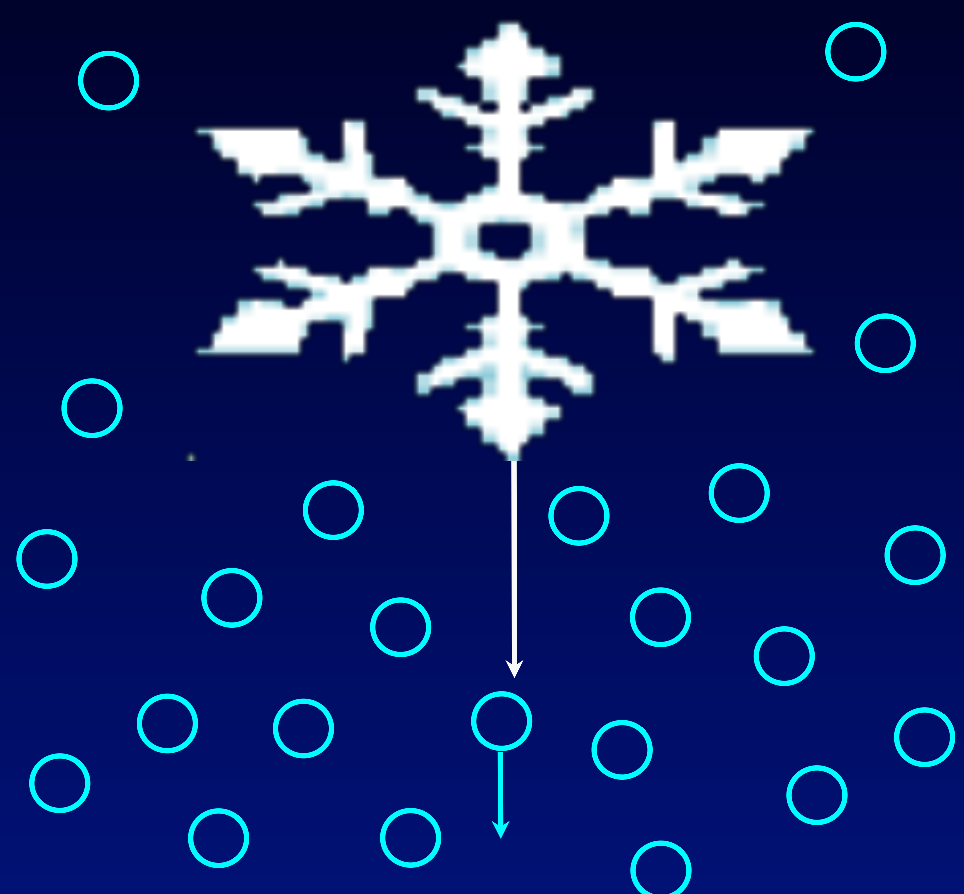
Growth by riming:

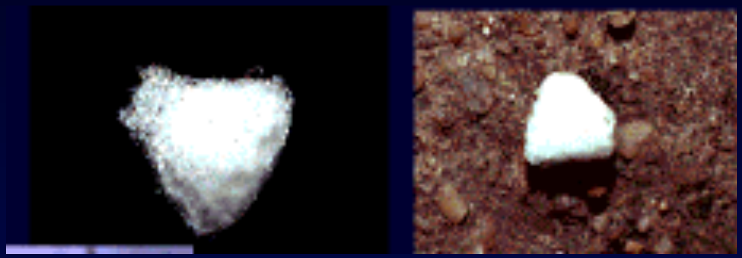
- Ice particles grow by colliding with super-cooled droplets that freeze onto them to form *rimed crystals* or *graupel.*
- *Hailstones* are the ultimate in riming growth.





Accretion (riming)





Graupel (UCLA)

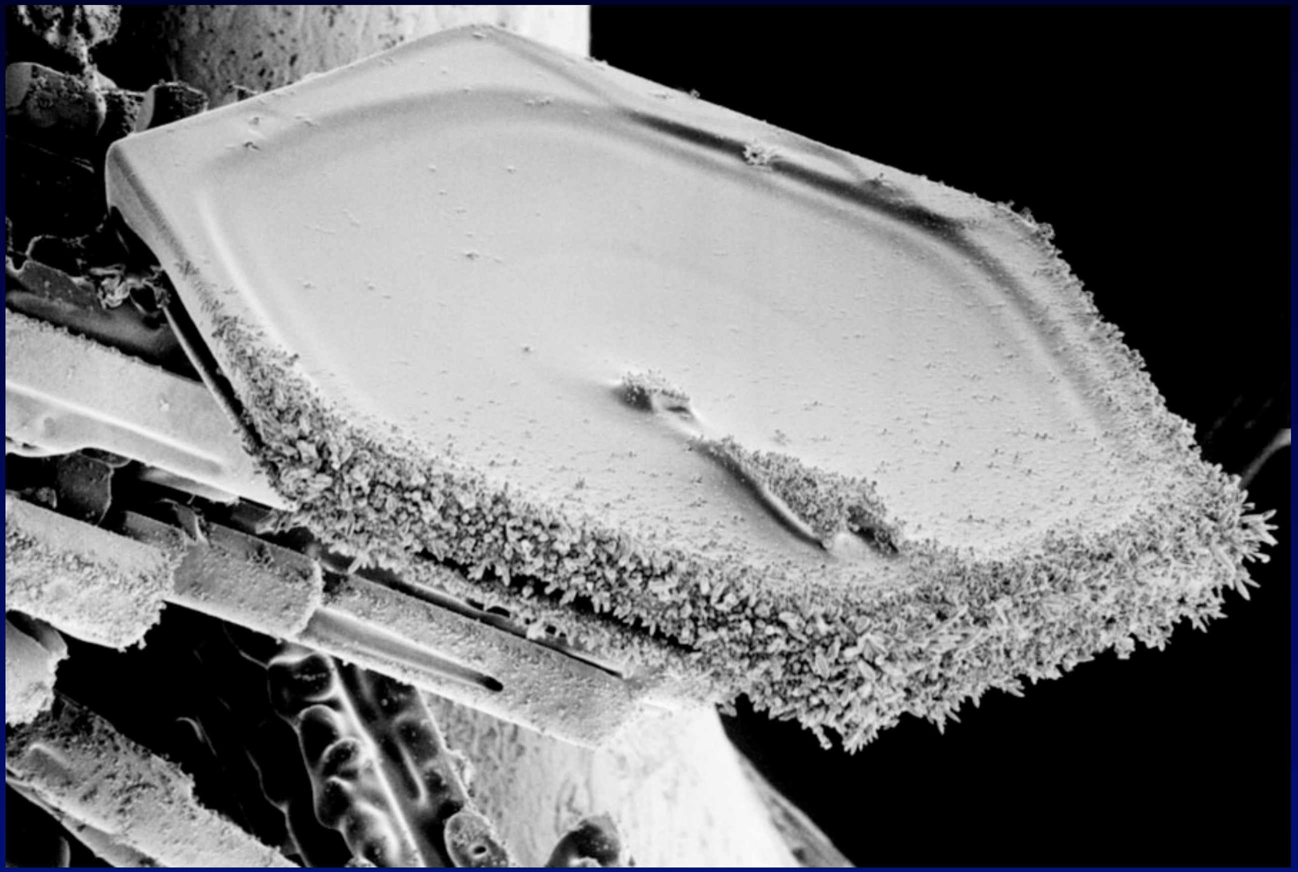
Magono and Lee (1966)

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

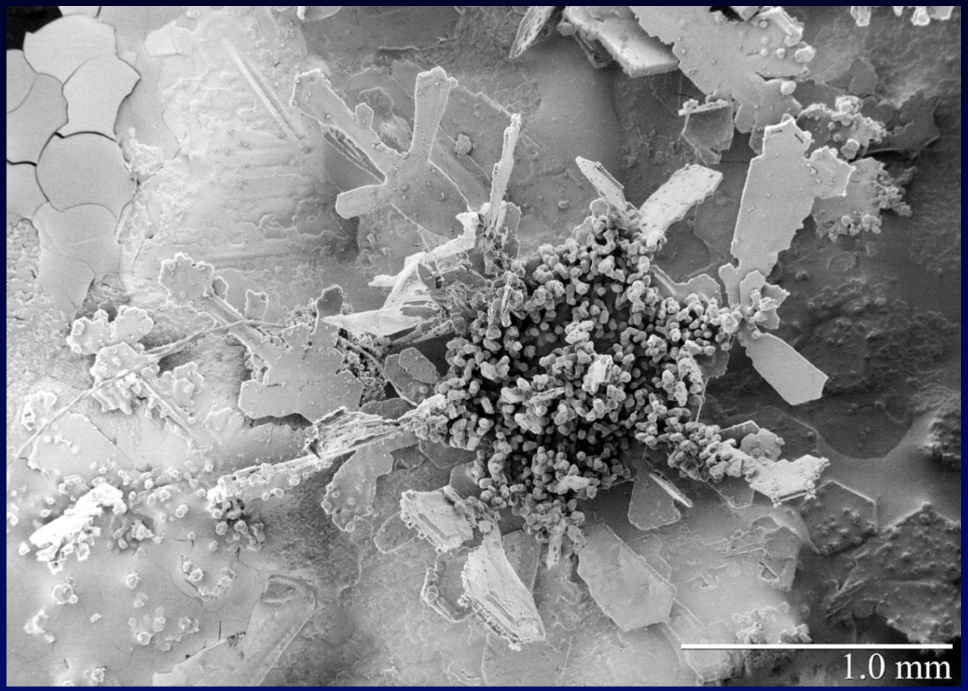
Riming

- 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)

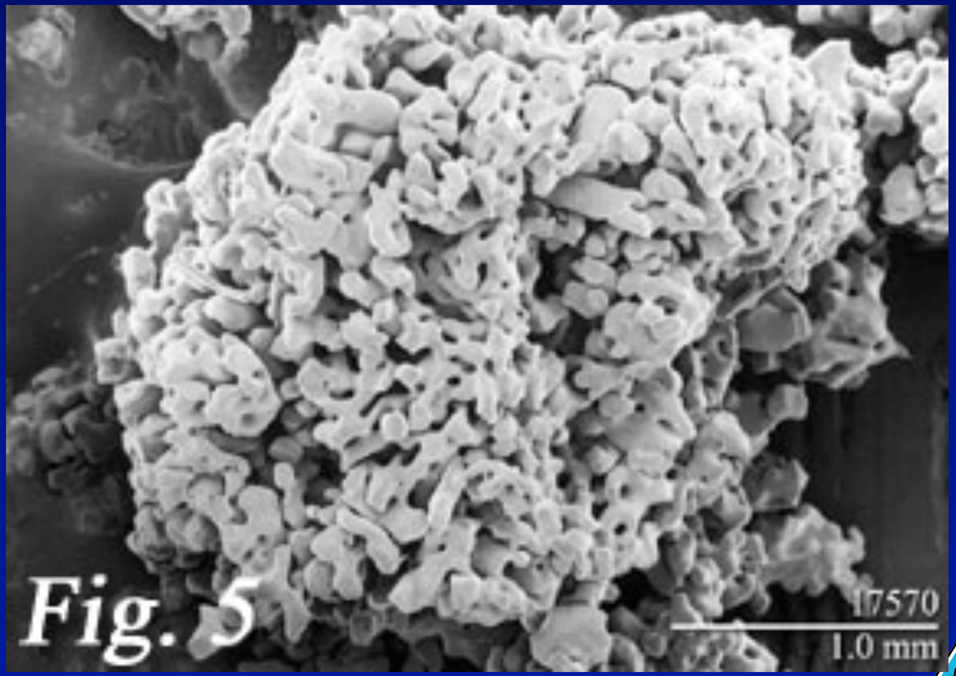
Accretion (riming)



Rimed Plate



Rimed Dendrite



Graupel

USDA Beltsville Agricultural Research Center

"Riming is not good for skiing"
- Jim Steenburgh

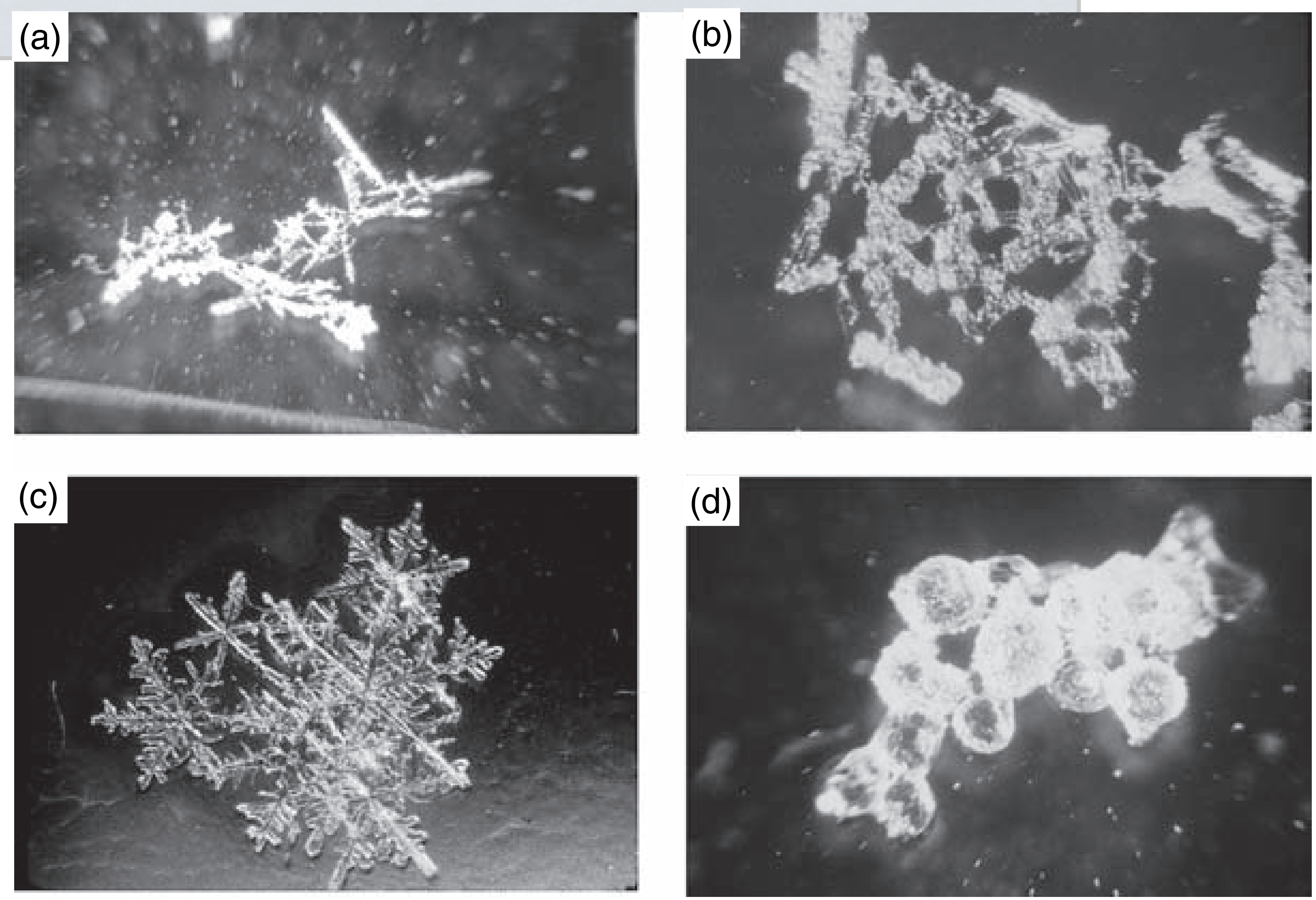
METEOROLOGY

Growth of Ice Particles in Clouds

Growth by aggregation:

- Ice particles can collide if their fall speeds differ.
  - The fall speed of plates does not depend on size.
  - The fall speeds of rimed crystals and graupel strongly depends on size.

- Probability of ice particles adhering after colliding depends on:
  - type of particle
  - temperature



Formation of Precipitation in Cold Clouds

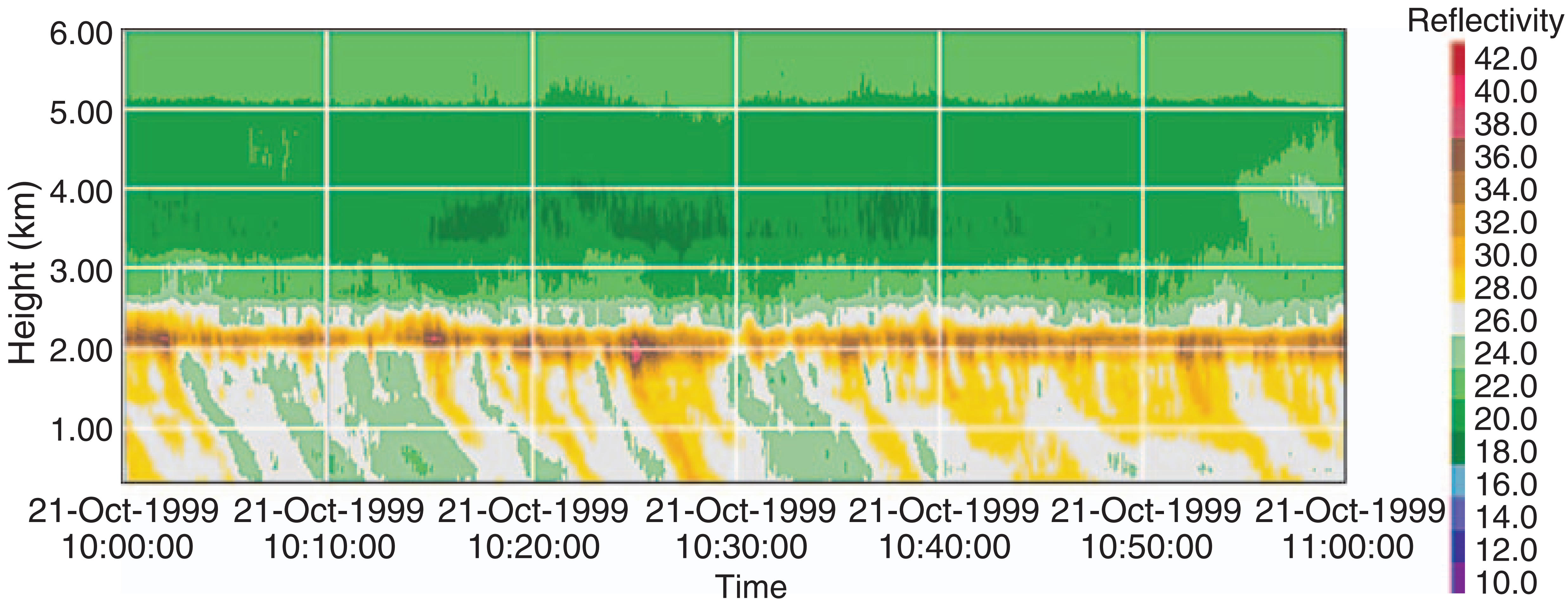
- **Growth by deposition**
  - Hexagonal plate; water saturation at T = -5°C
  - In 0.5 h: mass = 7 ug, r=0.5 mm (Ex. 6.27)
  - Melted radius = 130 um
  - Cannot produce large raindrops
- **Growth by riming**
  - Plate, 1 mm eff. diam, falls through cloud with LWC=0.5 g/m^3
  - In a few minutes: spherical graupel particle, r=0.5 mm, (Ex. 6.28)
  - Density = 100 kg/m^3, melted r=230 um
- **Growth by aggregation**
  - In 0.5 h: snowflake radius increases from 0.5 mm to 0.5 cm when IWC = 1 g/m^3
  - Mass = 3 mg, melted r=1 mm
- **Deposition followed by riming and/or aggregation can produce precipitation in about 40 minutes.**

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 (deposition)
  - 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

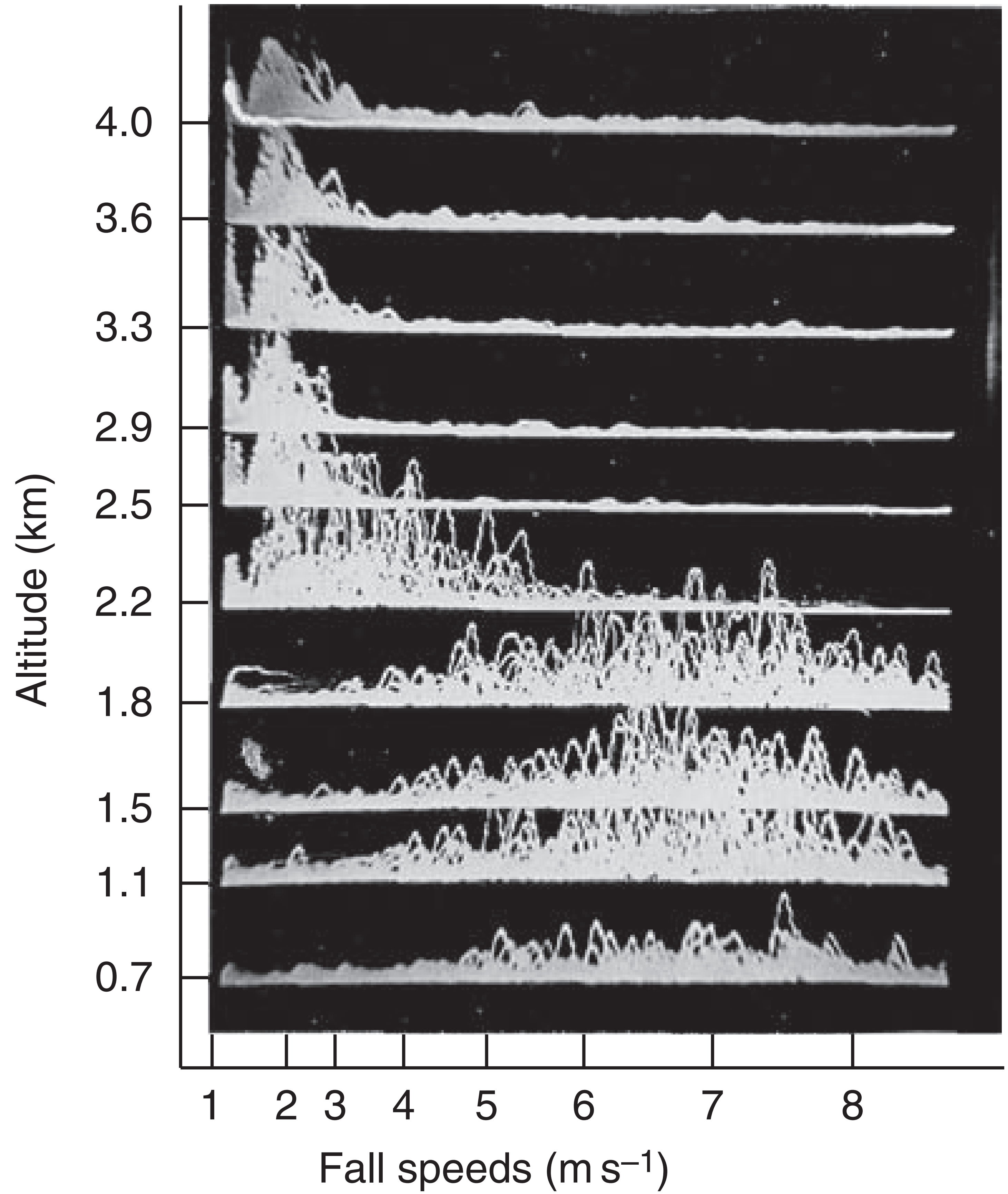
Formation of Precipitation in Cold Clouds

“Bright band” or melting band



Formation of Precipitation in Cold Clouds

Fall speeds increase below melting level (at 2.2 km)



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

Summary of how mother nature creates precipitation

- Condensational growth of cloud droplets
- Some growth of cloud droplets due to collision-coalescence
- Development of a mixed-phase cloud (glaciation)
- Crystal growth through vapor deposition
  - Most effective at –10 to –15 C
- Other possible effects
  - Accretion of supercooled cloud droplets onto 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, particularly at warm temperatures

METEOROLOGY