Cloud microphysics

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WS 2011/2012

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)
  - formation of rain, stochastical coalescence
- Microphysics of cold clouds
  - homogeneous, heterogeneous, and contact nucleation
  - concentration of ice particles in clouds
  - crystal growth (from vapor phase, riming, aggregation)
  - formation of precipitation
- Observation of cloud microphysical properties
- Parameterization of clouds in climate and NWP models

Homogeneous and heterogeneous nucleation

- measured median freezing temperatures
- homogeneous freezing
- heterogeneous freezing

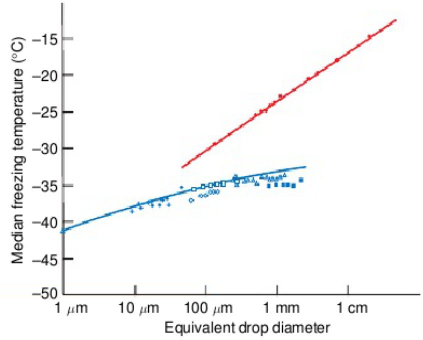


Fig. 6.29 Median freezing temperatures of water samples as a function of their equivalent drop diameter. The different symbols are results from different workers. The red symbols and red line represent heterogeneous freezing, and the blue symbols and line represent homogeneous freezing. [Adapted from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

Figure from Wallace and Hobbs

Further nucleation processes

Contact nucleation

Freezing starts when suitable particle (contact nucleus) comes into contact with super-cooled droplet.

Deposition

Some particles (deposition nuclei) serve as centers where ice forms directly from vapor phase. Conditions: air supersaturated w.r.t. ice and T sufficiently low

When air is supersaturated w.r.t. ice and water, some particles may act as freezing nucleus (vapor $\Rightarrow$liquid $\Rightarrow$ice) or as deposition nucleus (vapor $\Rightarrow$ice).

Onset of ice nucleation

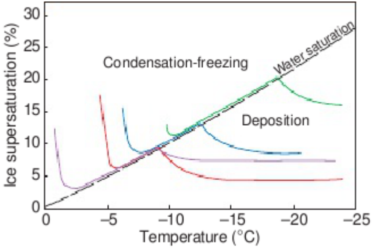


Fig. 6.30 Onset of ice nucleation as a function of temperature and supersaturation for various compounds. Conditions for condensation-freezing and ice deposition are indicated. Ice nucleation starts above the indicated lines. The materials are silver iodide (red), lead iodide (blue), methaldehyde (violet), and kaolinite (green). [Adapted from *J. Atmos. Sci.* **36**, 1797 (1979).]

Figure from Wallace and Hobbs

- Onset of of ice nucleation as function of temperature and supersaturation
- Onset occurs at higher T under water-supersaturated conditions
- Lower T required under water-subsaturated conditions, when only deposition is possible

Measurements of ice nucleus concentrations

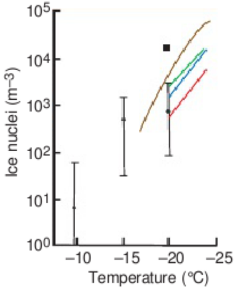


Fig. 6.31 Measurements of average ice nucleus concentrations at close to water saturation in the northern and southern hemispheres. Southern hemisphere, expansion chamber (red); southern hemisphere, mixing chamber (blue); northern hemisphere, expansion chamber (green); northern hemisphere, mixing chamber (black square); Antarctica, mixing chamber (brown). Vertical lines show the range and mean values (dots) of ice nucleus concentrations based on Millipore filter measurements in many locations around the world.

Figure from Wallace and Hobbs

Empirical relationship

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

T_1 – temperature at which 1 nucleus/liter is active (typically $\approx 20^\circ$C)

a – constant between 0.3 and 0.6, depending on conditions

e.g. a=0.6 $\Rightarrow$N increases by factor of 10 for every 4°decrease in T

Effect of supersaturation on ice nucleus concentration

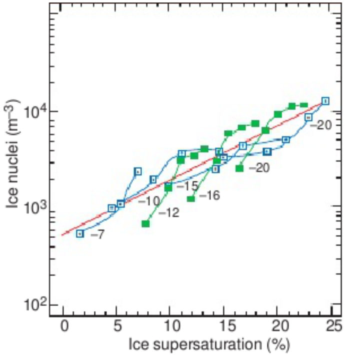


Fig. 6.32 Ice nucleus concentration measurements versus ice supersaturation; temperatures are noted alongside each line. The red line is Eq. (6.35). [Data reprinted from D. C. Rogers, "Measurements of natural ice nuclei with a continuous flow diffusion chamber," *Atmos. Res.* **29**, 209 (1993) with permission from Elsevier–blue squares, and R. Al-Naimi and C. P. R. Saunders, "Measurements of natural deposition and condensation-freezing ice nuclei with a continuous flow chamber," *Atmos. Environ.* **19**

The greater the supersaturation the more particles act as ice nuclei.

empirical fit:

$$N = \exp(a + b(100(S_i - 1)))$$

a=-0.639, b=0.1296

Maximum concentration of ice particles

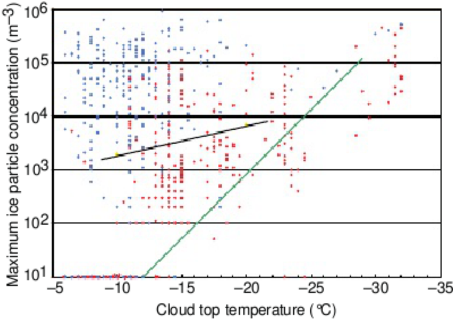


Fig. 6.34 Maximum concentrations of ice particles versus cloud top temperature in mature and aging marine cumuliform clouds (blue dots) and in continental cumuliform clouds (red dots). Note that on the abscissa temperatures decrease to the right. Symbols along the abscissa indicate ice concentrations ≤ 1 liter^{-1}, which was the lower limit of detection. The green line shows ice nucleus concentrations predicted by Eq. (6.33) with $a = 0.6$ and $T_1 = 253$ K. The black line shows ice nucleus concentrations from (6.35) assuming water-saturated conditions. [Data from *J. Atmos. Sci.* **42**, 2528 (1985); and *Quart. J. Roy. Met. Soc.* **117**, 207 (1991) and **120**, 573 (1994). Repro-

- empirical relation from laboratory measurements corresponds to minimum values of maximum concentrations
- concentrations in natural clouds can be several orders of magnitude larger !

Explanations for high ice crystal concentrations

- measurement techniques in laboratory can not be applied to natural clouds (conditions too different)
- ice multiplication or ice enhancement process
    - some crystals are fragile and may break up in several splinters when colliding with other particles
    - Super-cooled droplet freezes in isolation (e.g. free fall), or after it collides with an ice particle (i.e. riming – freezing of droplet on ice crystal) $\Rightarrow$freezing in 2 stages, particle may explode in 2nd stage of freezing

Stages of freezing

1. fine mesh of ice shoots through droplet and freezes just enough water to enhance temperature to 0°C (happens almost instantaneously)
2. 2nd stags of freezing much slower, heat is transferred from partially frozen droplet to colder ambient air
   - ice shell forms over surface of droplet and thickens progressively inward
   - water is trapped in interior $\Rightarrow$expands as it freezes $\Rightarrow$large stresses on ice shell
   - finally ice shall cracks or even explode $\Rightarrow$numerous small ice particles

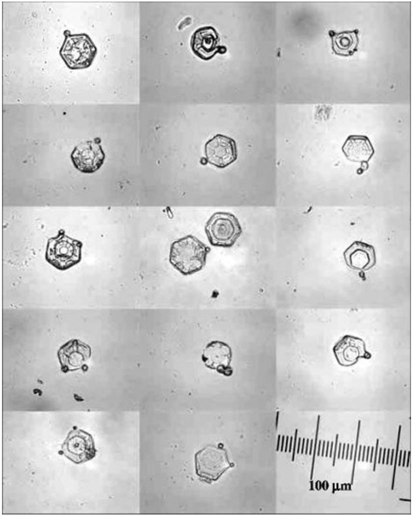
Riming

Riming

Freezing of droplet on ice crystal.

- riming might be most important for ice enhancement
- when ice particle falls through super-cooled cloud it is impacted by thousands of droplets, each may shed numerous ice splinters
- Laboratory measurement
  - Setup:
    - droplet concentration: 50/cm^3
    - droplet diameter: 5–35μm
    - liquid water content: 0.2 g/m^3
    - temperature: -4.5°C
    - impact speed: 3.6 m/s
  - 300 splinters are produced for every μg of accumulated rime

Riming



from Avila et al., 2009

Observation of ice crystal concentrations in clouds

- high concentrations of ice particles mainly found in older clouds
- young ($<$10 min) cumulus towers consist entirely of water droplets,
  after 10 min ice particles form rapidly
- high concentrations occur after formation of drops $> 25\mu$m and when rimed particles occur
  $\Rightarrow$consistent with hypothesis that riming is reason for high ice particle concentrations
- BUT: Riming process observed in laboratory much slower as in natural clouds, where an explosive formation of extremely high concentrations is observed
- Explosive formation of ice crystals not yet understood!

Ice development in small cumuliform clouds

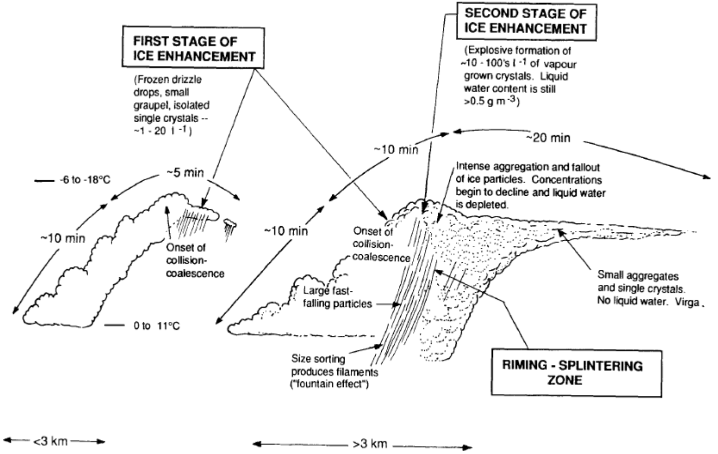


Figure 14. Schematic of observations and speculations presented in this paper on the formation of high ice particle concentrations in small polar maritime cumuliform clouds. The clouds on the right and left represent those indicated by A and B in Fig. 1.

from Rangno and Hobbs (1991)

Growth from the vapor phase in mixed-phase clouds

- mixed-phase cloud is dominated by super-cooled droplets
- air is close to saturated w.r.t. liquid water
- air is supersaturated w.r.t. ice

Example

T=-10°C, $RH_l \approx 100\%$, $RH_i \approx 110\%$
T=-20°C, $RH_l \approx 100\%$, $RH_i \approx 121\%$
$\Rightarrow$much greater supersaturations than in warm clouds

In mixed-phase clouds, ice particles grow from vapor phase much more rapidly than droplets.

Growth of ice crystal in supercooled water droplets

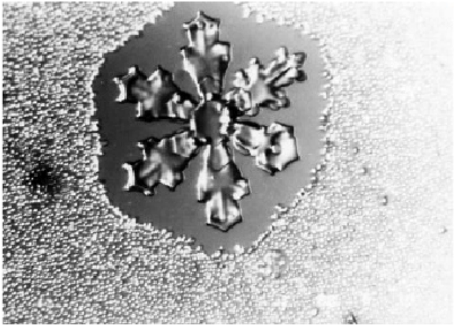


Fig. 6.36 Laboratory demonstration of the growth of an ice crystal at the expense of surrounding supercooled water drops. [Photograph courtesy of Richard L. Pitter.]

Figure from Wallace and Hobbs

growing ice crystal lowers vapor pressure in its vinvinity below saturation

⇒droplets evaporate

Mixed-phase cumulus clouds

Fig. 6.37 The growing cumulus clouds in the foreground with well-defined boundaries contained primarily small droplets. The higher cloud behind with fuzzy boundaries is an older glaciated cloud full of ice crystals. [Photograph courtesy

- cumulus turrets containing relatively large ice crystals and have fuzzy boundaries
- turrets containing small water droplets have well defined sharper boundaries

Fallstreaks of ice crystals

Fig. 6.38 Fallstreaks of ice crystals from cirrus clouds. The characteristic curved shape of fallstreaks indicates that the wind speed was increasing (from left to right) with increasing altitude. [Photograph courtesy of Art Rangno.]

- since equilibrium vapor pressure over ice is lower than over water, ice crystals evaporate slower and may migrate for larger distances into subsaturated air surrounding the cloud
- large ice crystals may fall out of clouds and survive great distances before they evaporate completely, even if ambient air is subsaturated w.r.t. ice
- trails of ice are called fallstreaks or virga

Shapes of ice crystals

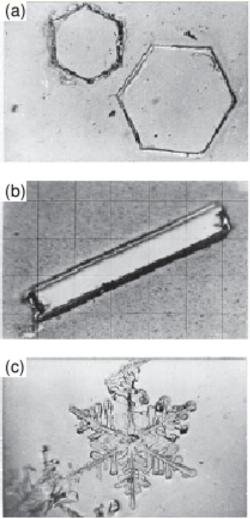


Figure from Wallace and Hobbs

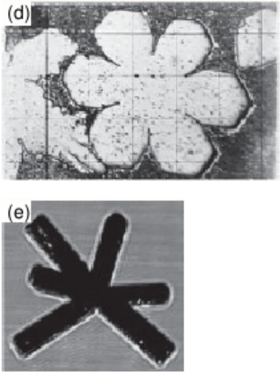


Fig. 6.40 Ice crystals grown from the vapor phase: (a) hexagonal plates, (b) column, (c) dendrite, and (d) sector plate. [Photographs courtesy of Cloud and Aerosol Research Group, University of Washington.] (e) Bullet rosette. [Photograph courtesy of A. Heymsfield.]

Schematic representation of ice crystals

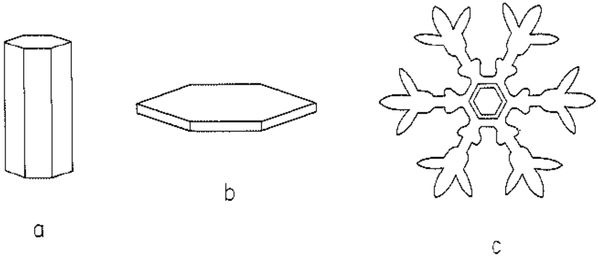


FIG. 8.3. Schematic representation of the main shapes of ice crystals: (a) column; (b) plate; (c) dendrite.

Figure from Rogers

Mass growth rate of an ice crystal

- diffusional growth of ice crystal similar to growth of droplet by condensation
- more complicated, mainly because ice crystals are not spherical $\Rightarrow$points of equal water vapor do not lie on a sphere centered on crystal

$$\frac{dM}{dt} = 4\pi CD\left(\rho_v(\infty) - \rho_{vc}\right)$$

Mass growth rate of an ice crystal

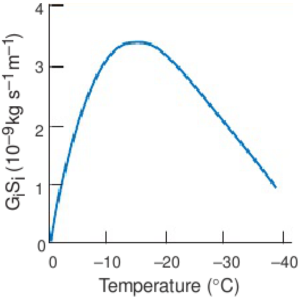


Fig. 6.39 Variation of G_iS_i [see Eq. (6.37)] with temperature for an ice crystal growing in a water-saturated environment at a total pressure of 1000 hPa.

Figure from Wallace and Hobbs

Approximate form:

$$\frac{dM}{dt} = 4\pi C G_i S_i$$

- Maximum growth rate at about -14°C

Mass growth rate of an ice crystal

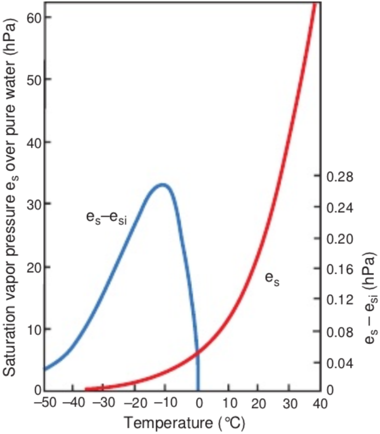


Fig. 3.9 Variations with temperature of the saturation (i.e., equilibrium) vapor pressure e_s over a plane surface of pure water (red line, scale at left) and the difference between e_s and the saturation vapor pressure over a plane surface of ice e_{si} (blue line, scale at right).

Figure from Wallace and Hobbs

Maximum growth rate at about -14°C

⇒difference between saturated pressures over water and ice is maximal at this temperature

⇒ice crystals grow most rapidly

Ice crystal shapes

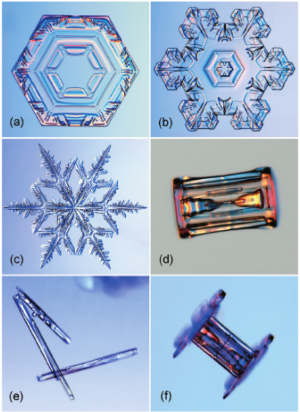


Figure 1. Examples of several different morphological types of snow crystals found in natural snowfalls in temperate climates. (*a*) A relatively simple plate-like crystal, 1.4 mm from tip to tip, showing fairly complex markings. Plates with smooth, featureless facets are less common in nature, except at low temperatures ($T \lesssim -20^\circ$C) and low humidities. (*b*) A more elaborate plate-like crystal, 2.1 mm from tip to tip, with an unusually high degree of complex symmetry. (*c*) A multi-branched stellar dendrite crystal, 3.0 mm from tip to tip. These typically form at higher humidities and only when the temperature is near $T = -15^\circ$C. (*d*) A simple hexagonal columnar crystal, 0.45 mm in length. Some internal hollowing resulted when the initially hollow ends of the column grew over. (*e*) Needle-like crystals, the largest being 1.1 mm in length. Note one needle grew as a slender hollow column before the ends branched. These crystals only grow near $T = -5^\circ$C. (*f*) A capped column crystal, 0.6 mm in length. This crystal began growing as a stout hollow column, and then plate-like stellar crystals grew on the two ends of the column. Photos by the author [16].

Figure from Libbrecht 2005

- ice crystals in natural clouds have mostly irregular shapes partly due to ice enhancement
- under appropriate conditions, ice crystals that grow from vapor phase can have a variety of regular shapes/habits (e.g. plate-like, column-like)

Ice crystal shapes

Laboratory studies and observations in natural cirrus clouds have shown that basic habit is determined by T at which crystal grows

Table 6.1 Variations in the basic habits of ice crystals with temperature[a]

		Supersaturation[b, c]	
Temperature (°C)	**Basic habit**	**Between ice and water saturation**	**Near to or greater than water saturation**
0 to −2.5	Plate-like	Hexagonal plates	Dendrites −1 to −2 °C
−3	Transition	Equiaxed	Equiaxed
−3.5 to −7.5	Column-like	Columns	Needles −4 to −6 °C Hollow columns −6 to −8 °C
−8.5	Transition	Equiaxed	Equiaxed
−9 to −40	Plate-like	Plates and multiple habits[d]	Scrolls and sector plates −9 to −12 °C Dendrites −12 to −16 °C Sector plates −16 to −20 °C
−40 to −60	Column-like	Solid column rosettes below −41 °C	Hollow column rosettes below −41 °C

[a] From information provided by J. Hallett and M. Bailey.
[b] If the ice crystals are sufficiently large to have significant fall speeds, they will be ventilated by the airflow. Ventilation of an ice crystal has a similar effect on embellishing the crystal habit, as does increasing the supersaturation.
[c] At low supersaturations, crystal growth depends on the presence of molecular defects. As water saturation is approached, surface nucleation occurs near the crystal edges and layers of ice spread toward the crystal interior. Growth at the edges of a crystal is limited by vapor and /or heat transfer and in the interior of a crystal by kinetic processes at the ice-vapor interface.
[d] At lower supersaturations different crystal habits grow under identical ambient conditions depending on the defect structure inherited at nucleation.

Table from Wallace and Hobbs

Morphology diagram

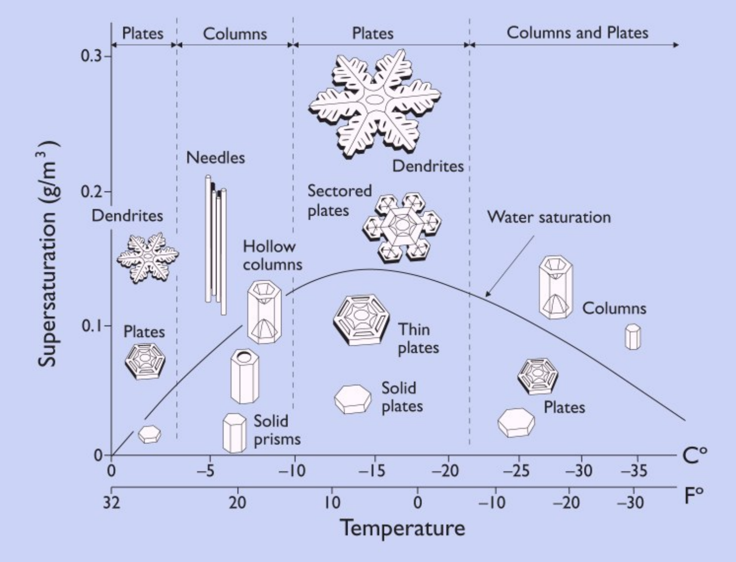


Figure from Libbrecht 2005

Morphology diagram

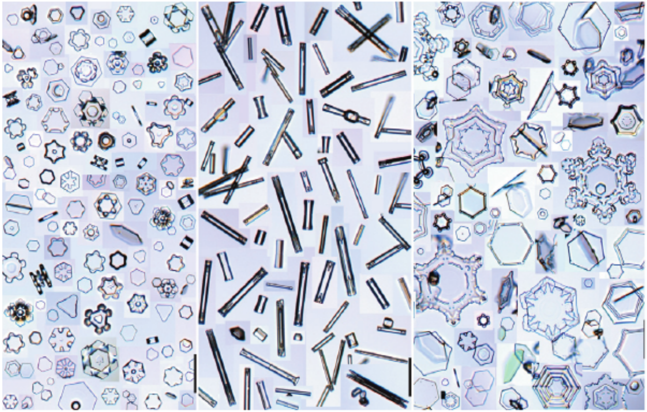


Figure 3. Examples of laboratory-made snow crystals grown at temperatures $T = -2^{\circ}$C (left), $T = -5^{\circ}$C (middle), and $T = -15^{\circ}$C (right) and supersaturations near water saturation [19]. Vertical scale bars are 100 μm long. These crystals were produced in a cold chamber filled with supersaturated air and photographed after they had fallen onto an observation window at the bottom of the chamber. Note the dramatic morphological changes from plates at -2°C to columns at -5°C to plates again at -15°C. Photos by the author [19].

Figure from Libbrecht 2005

Growth by accretion

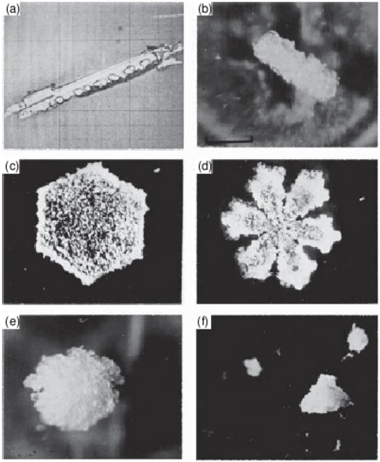


Fig. 6.41 (a) Lightly rimed needle; (b) rimed column; (c) rimed plate; (d) rimed stellar; (e) spherical graupel; and (f) conical graupel. [Photographs courtesy of Cloud and Aerosol Research Group, University of Washington.]

Figure from Wallace and Hobbs

- ice crystals falling through cloud of supercooled water droplets and other ice crystals may grow by accretion of water or of other ice crystals
- leads to rimed structures and graupel

Growth by aggregation

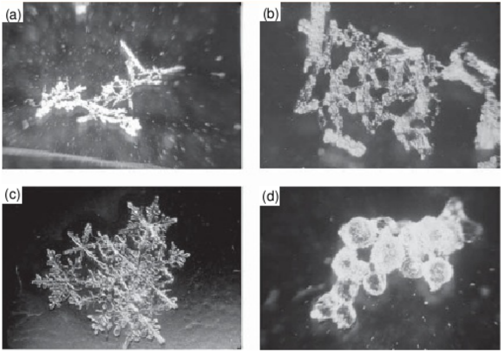


Fig. 6.44 Aggregates of (a) rimed needles; (b) rimed columns; (c) dendrites; and (d) rimed frozen drops. [Photographs courtesy of Cloud and Aerosol Research Group, University of Washington.]

Figure from Wallace and Hobbs

Snowflakes are formed by aggregation.

Terminal fall speed of ice crystals

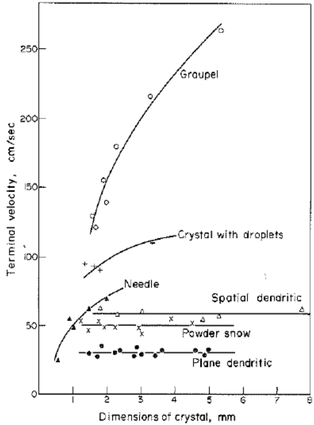


FIG. 8.5. Nakaya and Terada's measured terminal velocities of ice crystals. (From Fletcher, 1962.)

Figure from Rogers

Relation between crystal mass and maximum dimension of crystal

empirical relation by Mason (1971)

$$m = aD^b$$

TABLE 8.2. *Values of a and b in (8.7), for D in cm and m in g*

Crystal type	a	b
Graupel	0.065	3
Rimed plates and stellar dendrites	0.027	2
Powder snow and spatial dendrites	0.010	2
Plane dendrites	0.0038	2

Table from Rogers

Collection efficiency for accretion

collection efficiency = collision efficiency + coalescence efficiency

- can be determined theoretically for simple ice plates (Pitter and Pruppacher, 1974)
  - aerodynamic calculation of trajectories of water droplets relative to ice crystals
  - coalescence efficiency ≈ 1, because ice crytals are relatively small

Collection efficiency for aggregation

- not yet determined theoretically
- observations:
  - open structures (e.g. dendrites) more likely stick to other ice crystals
  - sticking more likely at higher temperatures
- $\Rightarrow$significant aggregation only at T $>$-10°C

Mass growth rate for accretional and aggregational growth

$$\frac{dm}{dt} = \bar{E} w_l \pi R^2 (v(R) - v(r))$$

$\bar{E}$ – mean collection efficiency
w_l – cloud liquid water content
v – fall speed of crystals / droplets
R – radius of collector crystal
r – radius of supercooled droplets

Same approach for aggregation, with w_l replaced by w_i (ice water content).

Hailstones

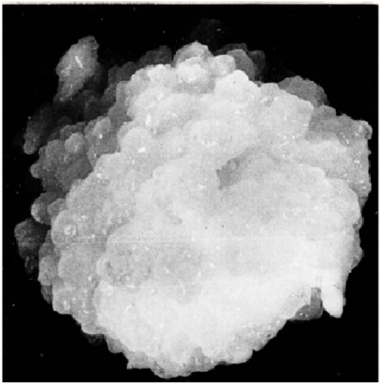


Fig. 6.43 Artificial hailstone (i.e., grown in the laboratory) showing a lobe structure. Growth was initially dry but tended toward wet growth as the stone grew. [Photograph courtesy of I. H. Bailey and W. C. Macklin.]

Figure from Wallace and Hobbs

- hailstone represents extreme case of growth of ice by riming
- largest reported hailstone: 13.8 cm diameter, 0.7 kg
- common hailstones: $\approx$ 1cm diameter
- hailstone collects supercooled water at high rate
  $\Rightarrow$T raises to 100°C
  $\Rightarrow$some water remains unfrozen
  $\Rightarrow$surface becomes covered with water and hailstone grows wet
- some of the water may be incorporated in ice $\Rightarrow$spongy hail

Hailstones

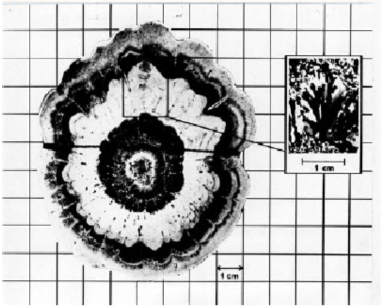


Fig. 6.42 Thin section through the center of a hailstone. [From *Quart. J. Roy. Met. Soc.* **92**, 10 (1966). Reproduced by permission of The Royal Meteorological Society.]

Figure from Wallace and Hobbs

- dark – opaque ice containing numereous small air bubbles
- light – clear (bubble-free) ice
- clear ice more likely forms when hailstone is growing wet
- surface may contain fairly large lobes