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
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)
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*
    - water supersaturated: vapor condenses onto *freezing nuclei* then freezes
    - water subsaturated: vapor deposits onto *deposition nuclei* as ice

![Graph showing ice supersaturation as a function of temperature](image)

- *silver iodide*
- *lead iodide*
- *methaldehyde*
- *kaolinitite*
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):

\[ \ln N = a + b [100(S_i - 1)] \]
Concentrations of Ice Particles

- Ice particles occur more frequently as $T$ decreases below $0^\circ$C.
Concentrations of Ice Particles

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

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

\[ \ln N = a(T_1 - T) \]
Concentrations of Ice Particles

Ice development in small cumulus clouds

ICE ENHANCEMENT

Frozen drizzle drops and/or small graupel, isolated single and irregular ice crystals ~0.1–20 per liter.

~5 to ~20°C

~10 min

Formation of drops ≥25 μm diameter.

~5 min

Formation of drops ≥25 μm diameter.

~10 min

Formation of drops ≥25 μm diameter.

~10 min

Large fast-falling ice particles.

Particle size sorting produces filaments and virga.

<3 km

~10 min

~20 min

Intense aggregation and fallout of ice particles. Concentrations of ice particles begin to decline and liquid water is depleted.

>3 km

“SUPER” ICE ENHANCEMENT

Explosive formation of ~10–100’s per liter of regular and irregular crystals. Liquid water content >0.5 g m⁻³.

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.
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

- Glaciated: ice crystals
- Small droplets
- Fallstreaks of ice crystals

This analogy was suggested by Harold Jeffreys. 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 of Art Rangno.]

Cumulus turrets containing relatively large ice crystals. [Photograph courtesy of Art Rangno.]

The leakage of charge or from an ice crystal is proportional to the electrostatic potential around a charged conductor of arbitrary shape by exploiting the analogy between the vapor field around an ice crystal and the field of static capacity.

\[ \frac{dM}{dt} = \frac{C}{V} (v_c - \eta R) \]

where \( C \) is the static capacity of the conductor, which is entirely defined in Section 6.4.1. We can derive an expression for the rate of increase in the mass of an ice crystal of arbitrary shape.

For the special case of spherical ice particle of radius \( r \), we can write, by analogy with (6.19),

\[ v_c = \frac{\pi}{2} \rho g x \left( \frac{\rho_s}{\rho - \rho_s} \right) \]

where \( r = 2 \rho_s / (\rho + \rho_s) \), and \( \rho_s \) is the density of the solid ice crystal. The points of equal vapor density do not lie on a sphere centered on the crystal as they do for a droplet. For the special case of spherical ice particles, the points of equal vapor density are all located on a sphere concentric with the crystal.
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**

**Habits** – types of ice crystal shapes created by vapor deposition

Snowcrystals.net
Growth of Ice Particles in Clouds

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

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Basic habit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to -2.5</td>
<td>Plate-like</td>
</tr>
<tr>
<td>-3</td>
<td>Transition</td>
</tr>
<tr>
<td>-3.5 to -7.5</td>
<td>Column-like</td>
</tr>
<tr>
<td>-8.5</td>
<td>Transition</td>
</tr>
<tr>
<td>-9 to -40</td>
<td>Plate-like</td>
</tr>
<tr>
<td>-40 to -60</td>
<td>Column-like</td>
</tr>
</tbody>
</table>
Vapor deposition (Bergeron-Findeisen Process)

- 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.

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**Figure 6.42**
- Growth by riming
- (a) Hailstones
- (b) Spherical graupel
- (c) Dendrites
- (d) Conical graupel
- (e) Plate-like ice crystals
- (f) Hollow column rosettes

---

**Figure 6.43**
- Artificial hailstone (i.e., grown in the laboratory)

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**Table 6.1**
- | Temperature | Basic Habit |
- |---|---|
- | 0 to 2°C | Plate-like Hexagonal plates |
- | 2 to 6°C | Dendrites |
- | 6 to 9°C | Sector plates |
- | 9 to 12°C | Scrolls and sector plates |
- | 12 to 20°C | Plate-like ice crystals |
- | 20°C | Hollow column rosettes |

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From information provided by J. Hallett and M. Bailey.
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

USDA Beltsville Agricultural Research Center

“Riming is not good for skiing”
- Jim Steenburgh

Rimed Dendrite

Graupel
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 depend on size.

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

[Images of ice particle aggregates]
Formation of Precipitation in Cold Clouds

- **Growth by deposition**
  - Hexagonal plate; water saturation at $T = -5\,^\circ\text{C}$
  - In 0.5 h: mass $= 7\,\text{ug}$, $r=0.5\,\text{mm}$ (Ex. 6.27)
  - Melted radius $= 130\,\text{um}$
  - Cannot produce large raindrops

- **Growth by riming**
  - Plate, 1 mm eff. diam, falls through cloud with LWC$=0.5\,\text{g/m}^3$
  - In a few minutes: spherical graupel particle, $r=0.5\,\text{mm}$, (Ex. 6.28)
  - Density $= 100\,\text{kg/m}^3$, melted $r=230\,\text{um}$

- **Growth by aggregation**
  - In 0.5 h: snowflake radius increases from 0.5 mm to 0.5 cm when $\text{IWC} = 1\,\text{g/m}^3$
  - Mass $= 3\,\text{mg}$, melted $r=1\,\text{mm}$

- **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

Cloud Microphysics was studied quantitatively and indicated the importance of ice nuclei in the formation of crystals. Because Findeisen conducted his field studies in northwestern Europe, he believed all rain originates as ice. However, as shown in Section 6.4.2, rain can also form in warm clouds by the collision-coalescence mechanism.

We will now consider the growth of ice particles to precipitation size in a little more detail. Application of (6.36) to the case of a hexagonal plate growing by deposition from the vapor phase in air saturated with respect to water at $H_{11002}$ shows that the plate can obtain a mass of $H_{11011}$ in half an hour (see Exercise 6.27). Thereafter, its mass growth rate decreases significantly. On melting, a 7-g ice crystal would form a small drizzle drop about 130 m in radius, which could reach the ground, provided that the updraft velocity of the air were less than the terminal fall speed of the crystal (about 0.3 m s$^{-1}$) and the drop survived evaporation as it descended through the subcloud layer. Calculations such as this indicate that the growth of ice crystals by deposition of vapor is not sufficiently fast to produce large raindrops.

Unlike growth by deposition, the growth rates of an ice particle by riming and aggregation increase as the ice particle increases in size. A simple calculation shows that a plate-like ice crystal, 1 mm in diameter, falling through a cloud with a liquid content of 0.5 g m$^{-3}$, could develop into a spherical graupel particle about 0.5 mm in radius in a few minutes (see Exercise 6.28). A graupel particle of this size, with a density of 100 kg m$^{-3}$, has a terminal fall speed of about 1 m s$^{-1}$ and would melt into a drop about 230 m in radius. The radius of a snowflake can increase from 0.5 mm to 0.5 cm in 30 min due to aggregation with ice crystals, provided that the ice content of the cloud is about 1 g m$^{-3}$ (see Exercise 6.29). An aggregated snow crystal with a radius of 0.5 cm has a mass of about 3 mg and a terminal fall speed of about 1 ms$^{-1}$. Upon melting, a snow crystal of this mass would form a drop about 1 mm in radius. We conclude from these calculations that the growth of ice crystals, first by deposition from the vapor phase in mixed clouds and then by riming and/or aggregation, can produce precipitation-sized particles in reasonable time periods (say about 40 min).

The role of the ice phase in producing precipitation in cold clouds is demonstrated by radar observations. For example, Fig. 6.45 shows a radar screen (on which the intensity of radar echoes reflected from atmospheric targets are displayed) while the radar antenna was pointing vertically upward and clouds drifted over the radar. The horizontal band (in brown) just above a height of 2 km was produced by the melting of ice particles. This is referred to as the "bright band." The radar reflectivity is high around the melting level because, while melting, ice particles become coated with a film of water that increases their radar reflectivity greatly. When the crystals have melted completely, they collapse into droplets and their terminal fall speeds increase so that the concentration of
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