# Cloud microphysics

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# 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, cloud modification
- Observation of cloud microphysical properties
- Parameterization of clouds in climate and NWP models

# 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.

# 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

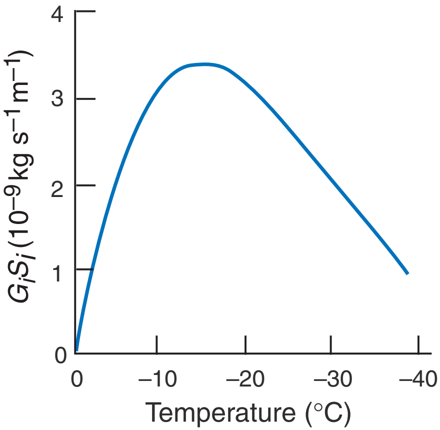



Figure from Wallace and Hobbs

**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

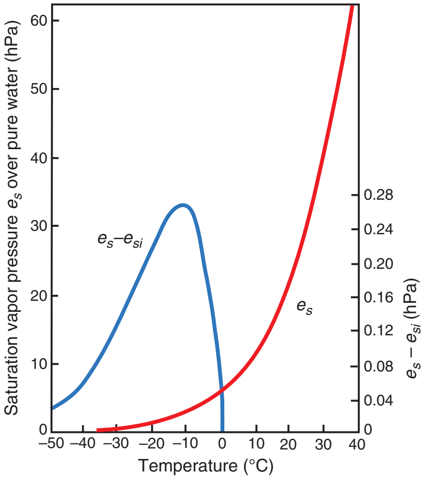



Figure from Wallace and Hobbs

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

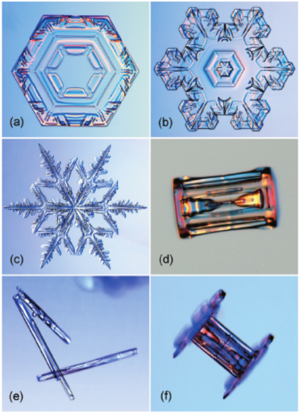



**Figure 1.** Examples of several different morphological types of snow crystals found in natural snowfalls in temperate climates. (*a*) A relatively simple plate-like crystal, 1.4 mm from tip to tip, showing fairly complex markings. Plates with smooth, featureless facets are less common in nature, except 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)

# Morphology diagram

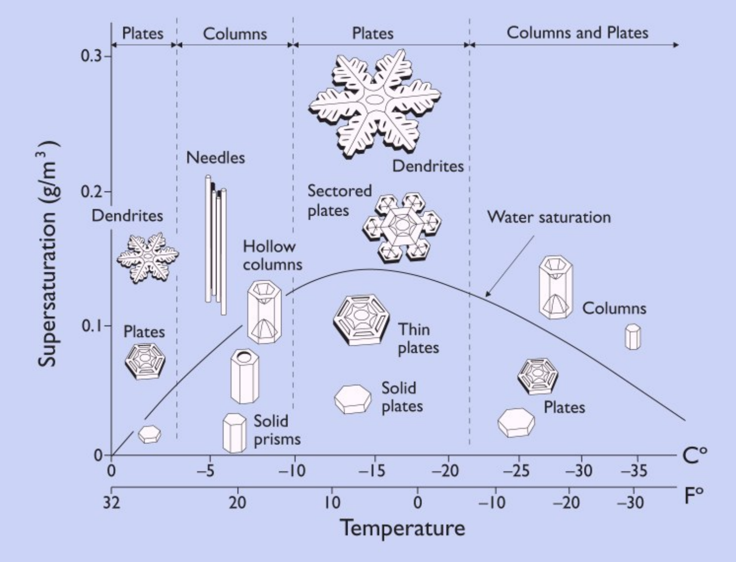



Figure from Libbrecht 2005

# Growth by accretion

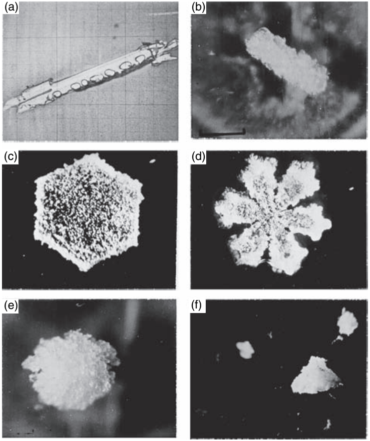



Figure from Wallace and Hobbs

- 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

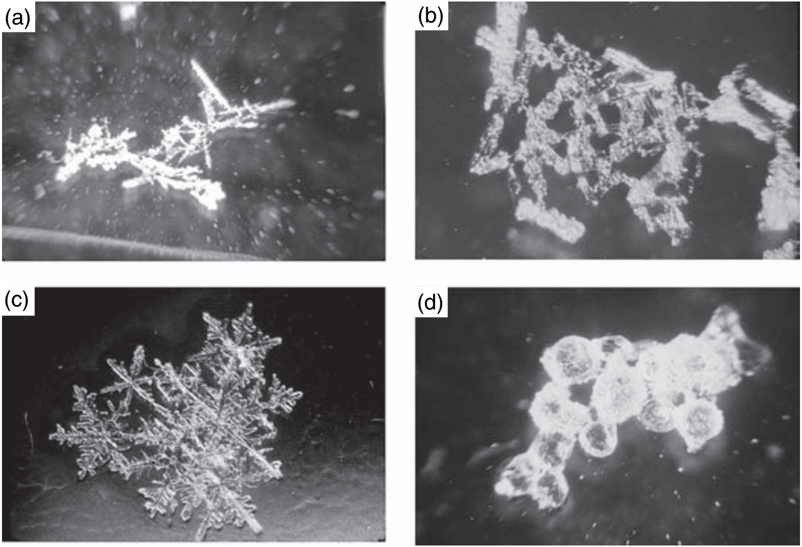



Figure from Wallace and Hobbs

# 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).

# Formation of precipitation in cold clouds

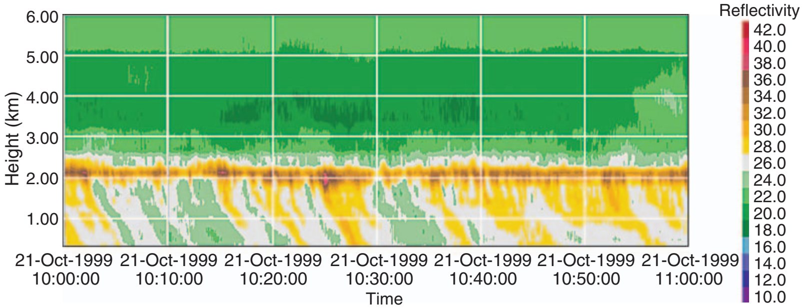
- 1789: Franklin suggested that “much of what is rain, when it arrives at the surface of the Earth might have been snow, when it began its descent ...”
- 1911: Wegener stated that ice particles grow preferentially by deposition from the water phase in mixed phase clouds.
- 1933: Bergeron, 1938: Findeisen
  First quantitative studies of formation of precipitation in cold clouds

## Bergeron-Findeisen Process

1. Deposition from vapor phase
2. Riming / aggregation

$\Rightarrow$precipitation sized particles can be produced in reasonable time periods.

# Radar reflectivity




Reflectivity (or "echo") from a vertically pointing radar.

Figure from Wallace and Hobbs, Courtesy of S.E. Yuter

The horizontal band of high reflectivity values (brown) is the melting band. The curved trails of relatively high reflectivity (yellow) emanating from the bright band are *fallstreaks* of precipitation, some of which reach the ground.

# Radar reflectivity

- bright band, melting band:
  radar reflectivity is high because, while melting, ice particles become coated with film of water that increases their radar reflectivity greatly.

- when ice crystals have melted completely, their terminal fall speed increases, concentration of particles decreases
  $\Rightarrow$sharp decrease in radar reflectivity below melting band

# Fall speeds

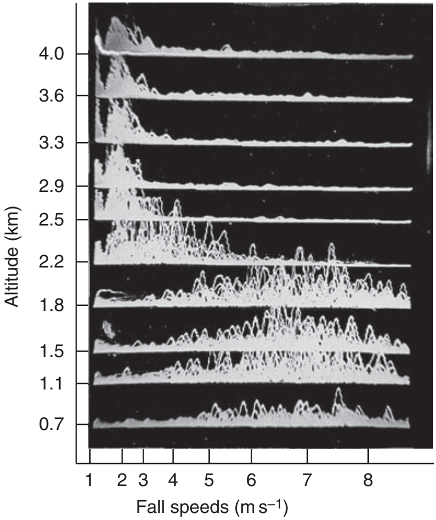


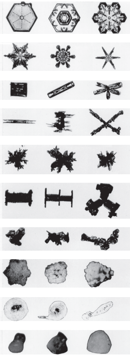

Figure from Wallace and Hobbs, Courtesy of Cloud and Aerosol Research Group, Uni Washington

- *Doppler radar*: Measures frequency difference between returned and transmitted waves $\Rightarrow$from this fall speed can be derived
- Spectra of fall speeds for precipitation particles at 10 heights.
- Melting level at about 2.2 km

# Classification of solid precipitation

**Table 6.2** A classification of solid precipitation[a,b,c]

Typical forms:



Graphic symbol:

| Symbol | Description |
|---|---|
| F1 | A plate is a thin, plate-like snow crystal the form of which more or less resembles a hexagon or, in rare cases, a triangle. Generally all edges or alternative edges of the plate are similar in pattern and length. |
| F2 | A stellar crystal is a thin, flat snow crystal in the form of a conventional star. It generally has 6 arms but stellar crystals with 3 or 12 arms occur occasionally. The arms may lie in a single plane or in closely spaced parallel planes in which case the arms are interconnected by a very short column. |
| F3 | A column is a relatively short prismatic crystal, either solid or hollow, with plane, pyramidal, truncated, or hollow ends. Pyramids, which may be regarded as a particular case, and combinations of columns are included in this class. |
| F4 | A needle is a very slender, needle-like snow particle of approximately cylindrical form. This class includes hollow bundles of parallel needles, which are very common, and combinations of needles arranged in any of a wide variety of fashions. |
| F5 | A spatial dendrite is a complex snow crystal with fern-like arms that do not lie in a plane or in parallel planes but extend in many directions from a central nucleus. Its general form is roughly spherical. |
| F6 | A capped column is a column with plates of hexagonal or stellar form at its ends and, in many cases, with additional plates at intermediate positions. The plates are arranged normal to the principal axis of the column. Occasionally, only one end of the column is capped in this manner. |
| F7 | An irregular crystal is a snow particle made up of a number of small crystals grown together in a random fashion. Generally the component crystals are so small that the crystalline form of the particle can only be seen with the aid of a magnifying glass or microscope. |
| F8 | Graupel, which includes soft hail, small hail, and snow pellets, is a snow crystal or particle coated with a heavy deposit of rime. It may retain some evidence of the outline of the original crystal, although the most common type has a form that is approximately spherical. |
| F9 | Ice pellets (frequently called sleet in North America) are transparent spheroids of ice and are usually fairly small. Some ice pellets do not have a frozen center, which indicates that, at least in some cases, freezing takes place from the surface inward. |
| F10 | A hailstone[d] is a grain of ice, generally having a laminar structure and characterized by its smooth glazed surface and its translucent or milky-white center. Hail is usually associated with those atmospheric conditions that accompany thunderstorms. Hailstones are sometimes quite large. |

[a] Suggested by the International Association of Hydrology's commission of snow and ice in 1951. [Photograph courtesy of V. Schaefer.]
[b] Additional characteristics: *p*, broken crystals; *r*, rime-coated particles not sufficiently coated to be classed as graupel; *f*, clusters, such as compound snowflakes, composed of several individual snow crystals; *w*, wet or partly melted particles.
[c] Size of particle is indicated by the general symbol D. The size of a crystal or particle is its greatest extension measured in millimeters. When many particles are involved (e.g., a compound snowflake), it refers to the average size of the individual particles.

[d] Hail, like rain, refers to a number of particles, whereas hailstone, like raindrop, refers to an individual particle.

Figure from Wallace and Hobbs

# Cloud seeding

Proposed techniques to artificially modify clouds and precipitation (cloud seeding):

- introduce large hygroscopic particles or water drops into warm clouds to stimulate growth of raindrops by collision/coalescence mechanism
- introduce artificial ice nuclei into cold clouds to stimulate precipitation by Bergeron-Findeisen process
- introduce high concentration of artificial ice nuclei into cold clouds
  $\Rightarrow$reduce drastically concentration of supercooled droplets
  $\Rightarrow$inhibit growth of ice particles
  $\Rightarrow$dissipate clouds and surpress growth of precipitable particles

# Modification of warm clouds

- introduction of water drops into tops of clouds not efficient for producing rain, because very large amount of water required
- introduction of small droplets (r≈30$\mu$m) or hygroscopic particles into base of cloud is more efficient:
  - particles grow by condensations as they are carried up
  - then grow by collision/coalescence when falling down

Several cloud seeding experiments have been carried out $\Rightarrow$so far no significant results

# Modification of cold clouds

Experiment by Langmuir and Schäfer (1946)

- Laboratory
  - when small piece of dry ice (e.g. $CO_2$) is dropped into cloud of supercooled droplets, numerous small ice crystals are produced and glaciated quickly
  - dry ice causes homogeneous nucleation since its temperature is -78°C
  - pellet of dry ice of 1cm diameter falling through air at -10°C produces approximately $10^{11}$ ice crystals
- Field experiment: Project Cirrus 1946
  - 1.5kg of crushed dry ice was dropped along line of 5km into layer of supercooled altocumulus cloud
  - snow was observed to fall out from the base of seeded cloud, evaporated 0.5km below cloud base

# Cloud overseeding

- because of large number of ice crystals that a small amount of dry ice may produce, method is suitably for overseeding the cloud
- overseeded cloud converts completely into ice crystals
- many small crystals, no supersaturated droplets, low supersaturation $\Rightarrow$crystals tend to evaporate

# Cloud overseeding with dry ice

Figure from Wallace and Hobbs, courtesy of General Electric Company, New York

- Photo: Path cut into a layer of supercooled cloud by seeding with dry ice.
- technique can also be used to dissipate supercooled fog, applied at airports

# Artificial ice nuclei

- Vonnegut searched for artificial ice nuclei in laboratory, found silver iodide to be appropriate (similar crystallographic structure)
- Cirrus Project (1948):
  - pieces of burning charcoal inpregnated with silver iodide were dropped from aircraft into supercooled stratus cloud (0.3 km thick, T=-10°C, area 16 $m^2$)
  - cloud was converted into ice by less than 30g AgI

# Modification of cold clouds

Many experiments have been performed

- Result: cloud seeding yields enhancement in ice crystal concentration

- Open question: Under which conditions (if any) can seeding with artificial ice nuclei be employed to produce significant increases in precipitation on the ground in predictable manner and over a large area?

# Other mechanisms

- overseeding $\Rightarrow$ cloud becomes glaciated $\Rightarrow$ release of latent heat $\Rightarrow$ buoyancy added to cloudy air
- might be sufficient to push cloud through inversion up to level of free convection

# Cloud overseeding

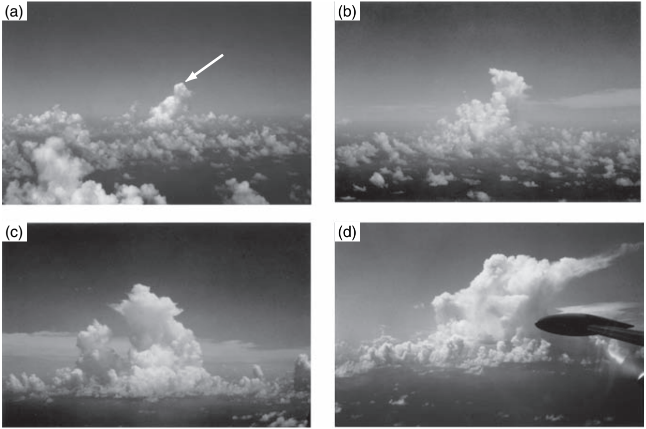



Figure from Wallace and Hobbs, courtesy of J. Simpson

Causality or coincidence? Explosive growth of cumulus cloud (a) 10 min, (b) 19 min, (c) 29 min, (d) 48 min.

# Cloud seeding to reduce damage by hailstones

- more ice nuclei $\Rightarrow$increase number of small particles $\Rightarrow$competition for available supercooled droplets $\Rightarrow$average size of hailstones should be reduced

- Results of field experiements so far not encouraging!

# Redistribution of orographic snowfall

- rimed ice particles have relatively large terminal fall speeds ($\approx$ 1m/s) and follow steep trajectories to the ground
- overseeding eliminates supercooled droplets and reduces growth by riming:
  - particles grow by deposition from vapor phase, fall speed reduced by factor of $\approx$2
  - wind alofts may carry crystals further before they reach ground

# Cloud seeding

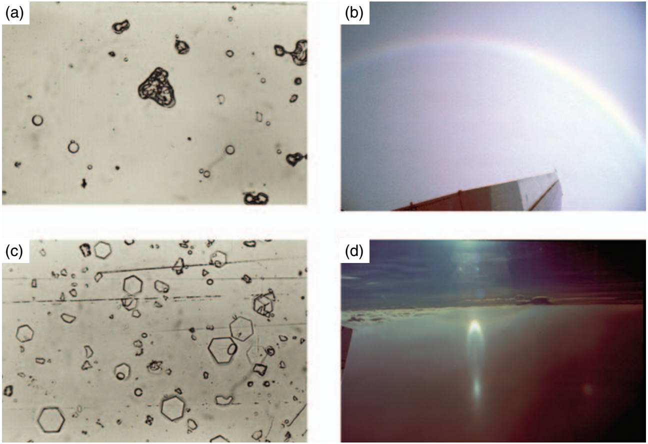



Figure from Wallace and Hobbs, Courtesy of Cloud and Aerosol Reasearch Group, University of Washington

(a) large rimed irregular particles collected in unseeded cloud, (b) cloud bow, due to supercooled droplets in unseeded cloud, (c) after seeding with artificial ice nuclei, cloud is converted into small unrimed plates, (d) halos visible due to ice crystal scattering

# Inadvertant cloud modification

Figure from Wallace and Hobbs, Courtesy of C.L. Hosler

Cloud in the valley in the background formed due to effluents from a paper mill. In the foreground, the cloud is spilling through a gap in the ridge into an adjacent valley.

Paper mills, burning of agricultural wastes and forest fires produce high concentrations of CCN.

# Holes in clouds


Figure from Wallace and Hobbs

**a** Holes are produced by removal of supercooed droplets by large amount of ice crystals ($\approx$ 100–1000 per liter)
ice crystals originate from a cloud above, cloud is intercepted by fallstreak

**b** produced by aircraft:

- ice crystals are produced by rapid expansion (and cooling) of air in vortices produced by wake of an aircraft
- if air is cooled below -40$^\circ$C, ice crystals are form by homogeneous freezing
- initially small crystals, grow at expense of supercooled droplets
- time between aircraft penetrating cloud and visible area of clear air: $\approx$10–20 min.