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In this section we are concerned with the origins and concentrations of ice particles in clouds, the ways ice particles grow, and the formation of precipitation in cold clouds.

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Hence, in the atmosphere, homogeneous nucleation of freezing occurs only in *high clouds*.

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Ice can form by deposition if the air is supersaturated with respect to ice and the temperature is low enough.

Ice Nuclei

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Some inorganic soil particles (mainly clays) can nucleate ice at fairly high temperatures (i.e., above $-15°$C), and play an important role in nucleating ice in clouds.

Measuring Ice Nuclei Concentration

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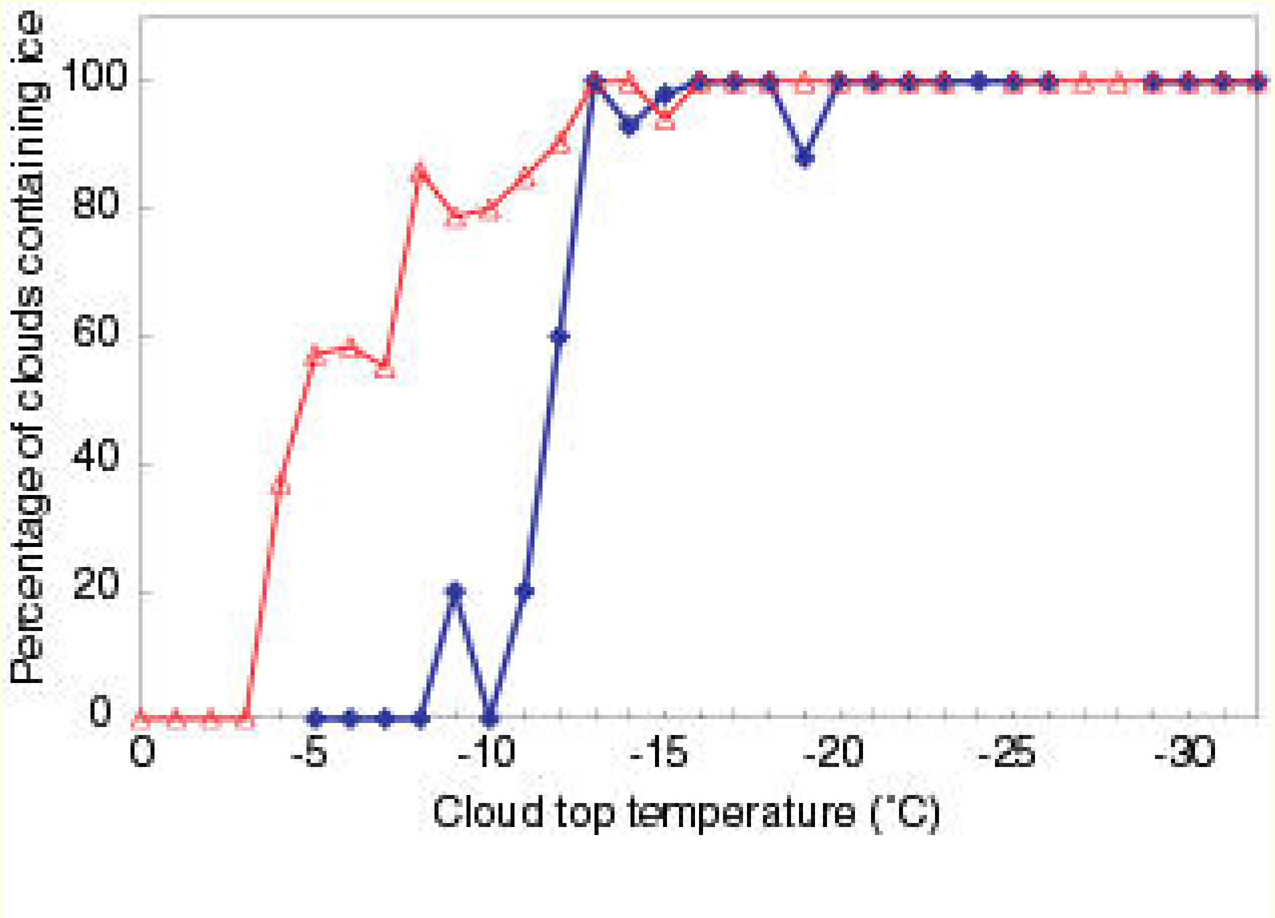
In *diffusion chambers* temperature, supersaturation and pressure can be controlled independently.

Concentrations of Ice Particles



Percentage of clouds containing ice particle concentrations greater than about 1 per liter as a function of cloud top temperature. Blue curve: Continental cumuliform clouds. Red curve: Clean marine cumuliform clouds and clean arctic stratiform clouds.

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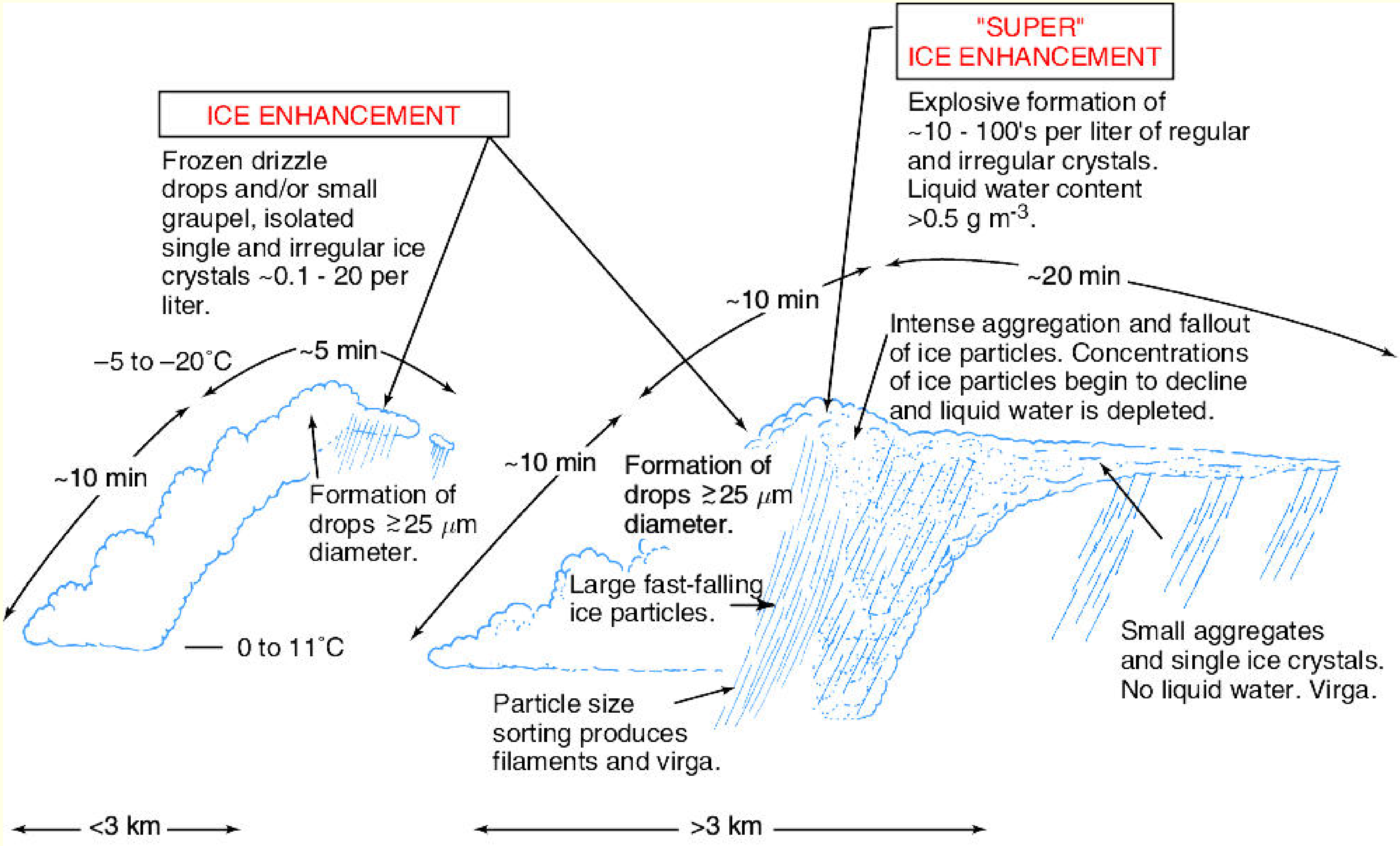
Clouds with top temperatures between about 0 and $-8°$C generally contain copious supercooled droplets. It is in clouds such as these that aircraft are most likely to encounter *severe icing* conditions, since supercooled droplets freeze when they collide with an aircraft.

Growth of Ice Particles in Clouds

We consider several methods of growth:

- **(a) Growth from the vapour phase.**
- **(b) Growth by riming; hailstones.**
- **(c) Growth by aggregation.**



Schematic of ice development in small cumuliform clouds.

(a) *Growth from the vapour phase.*

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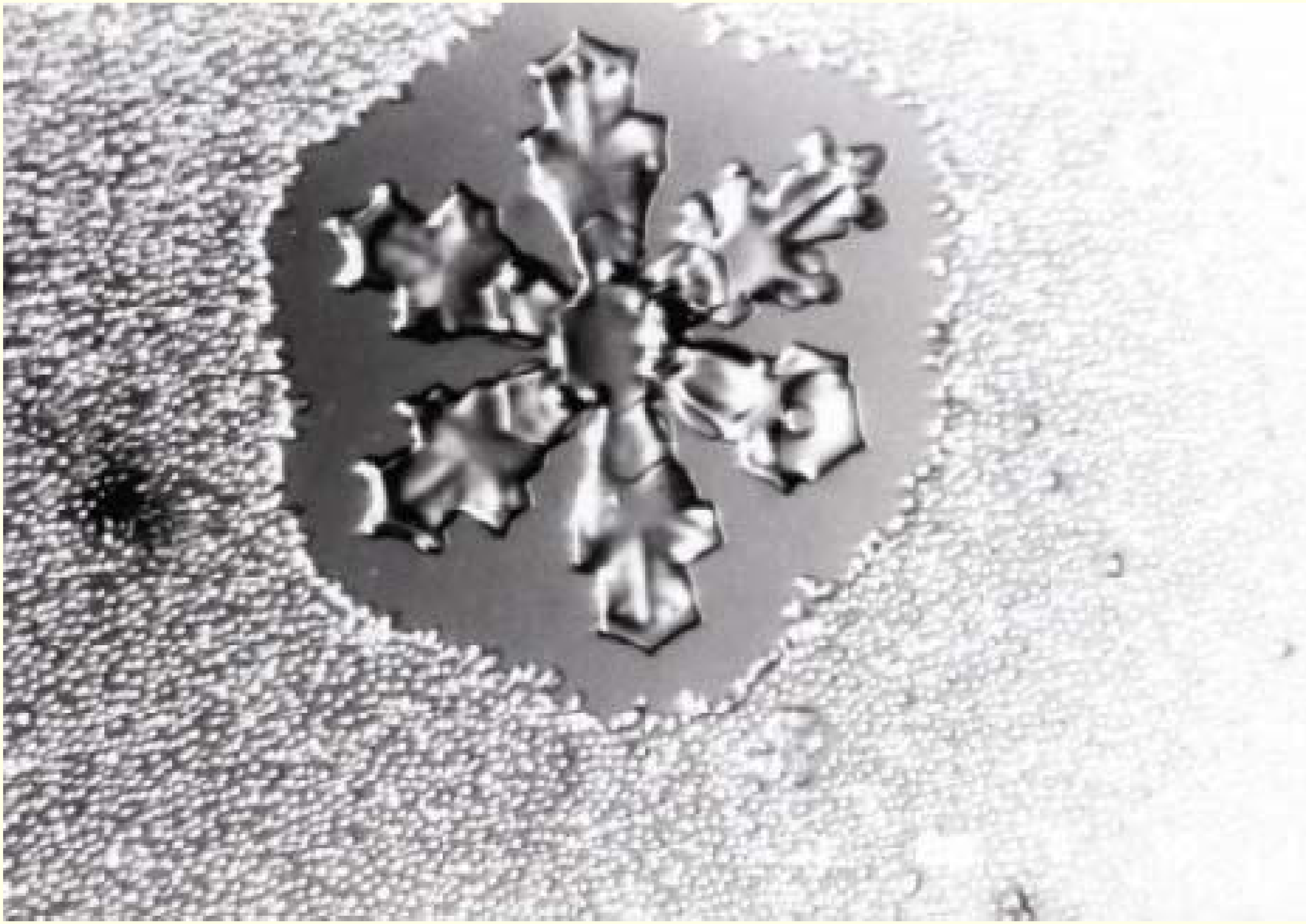
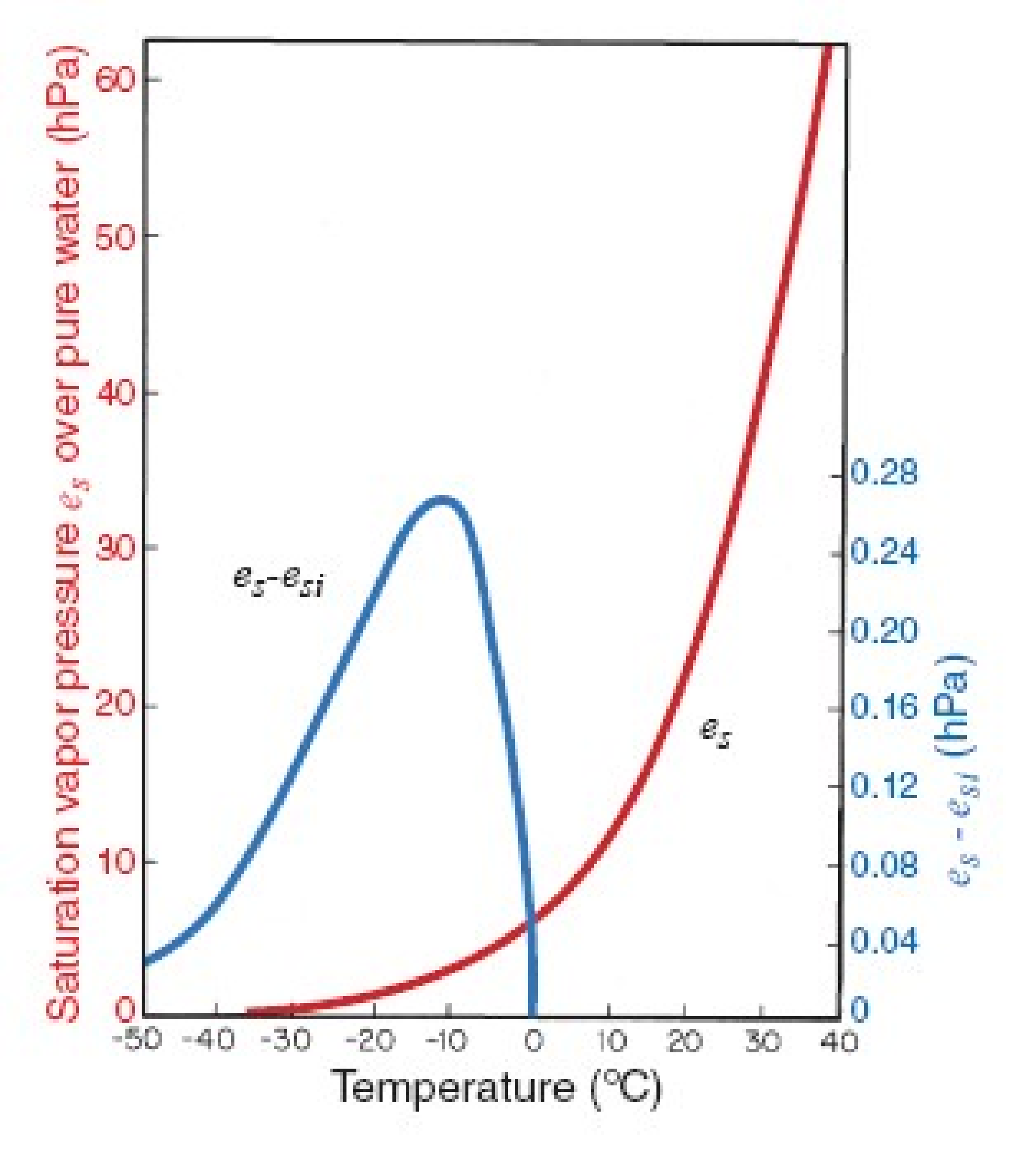
In fact, if a growing ice particle lowers the vapour pressure in its vicinity below water saturation, adjacent droplets will evaporate (Figure below).



Laboratory demonstration of the growth of an ice crystal at the expense of surrounding supercooled water drops.

Cumulus turrets containing relatively large ice particles often have ill defined, fuzzy boundaries, as for the clouts in the background here.

Turrets containing only small droplets have well-defined, sharper boundaries, particularly if the cloud is growing (see cloud in foreground).



Saturation vapour pressure over water (Red) and the difference between the saturation pressures over water and over ice (Blue).

The lower equilibrium vapour pressure over ice than over water at the same temperature allows ice particles to migrate for greater distances than droplets into the non-saturated air surrounding a cloud before they evaporate.

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Ice particles will grow in air that is sub-saturated with respect to water, provided that it is supersaturated with respect to ice.

Fallstreaks of ice crystals from cirrus clouds. The characteristic curved shape of the fallstreaks indicates that the wind speed was increasing (from left to right) with increasing altitude.

Shape and Form of Ice particles

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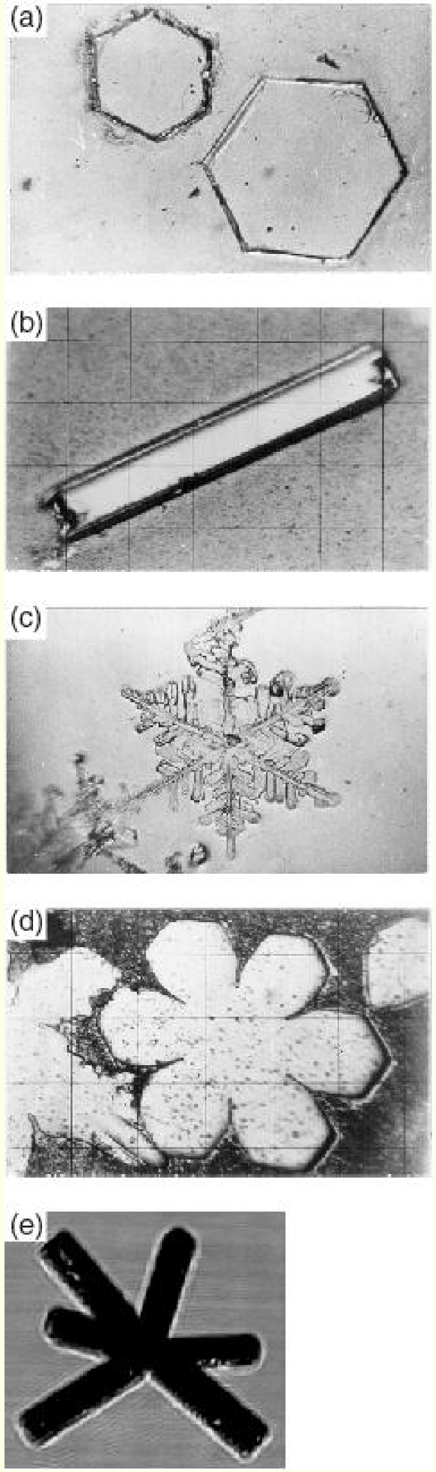
The simplest platelike crystals are plane *hexagonal plates*, and the simplest columnlike crystals are solid columns that are hexagonal in cross section.



Ice crystals grown from the vapour phase:
(a) hexagonal plates,
(b) column,
(c) dendrite,
(d) sector plate,
(e) bullet rosette.

(b) *Growth by riming; hailstones.*

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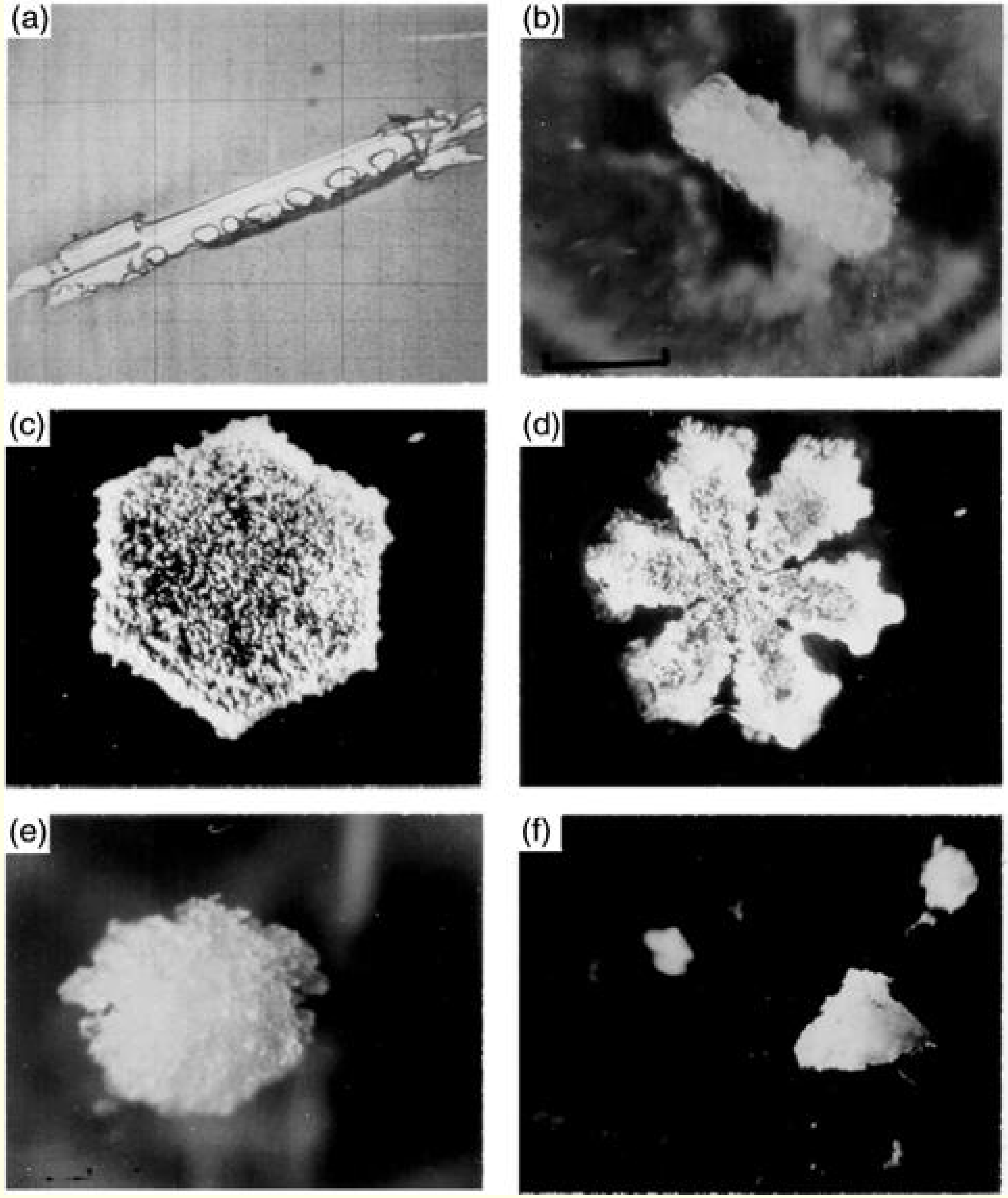
This process, referred to as *growth by riming*, leads to the formation of various rimed structures (figure follows).

When riming proceeds beyond a certain stage it becomes difficult to discern the original shape of the ice crystal. The rimed particle is then referred to as *graupel*.



(a) Lightly rimed needle; (b) rimed column; (c) rimed plate; (d) rimed stellar; (e) spherical graupel; (f) conical graupel.

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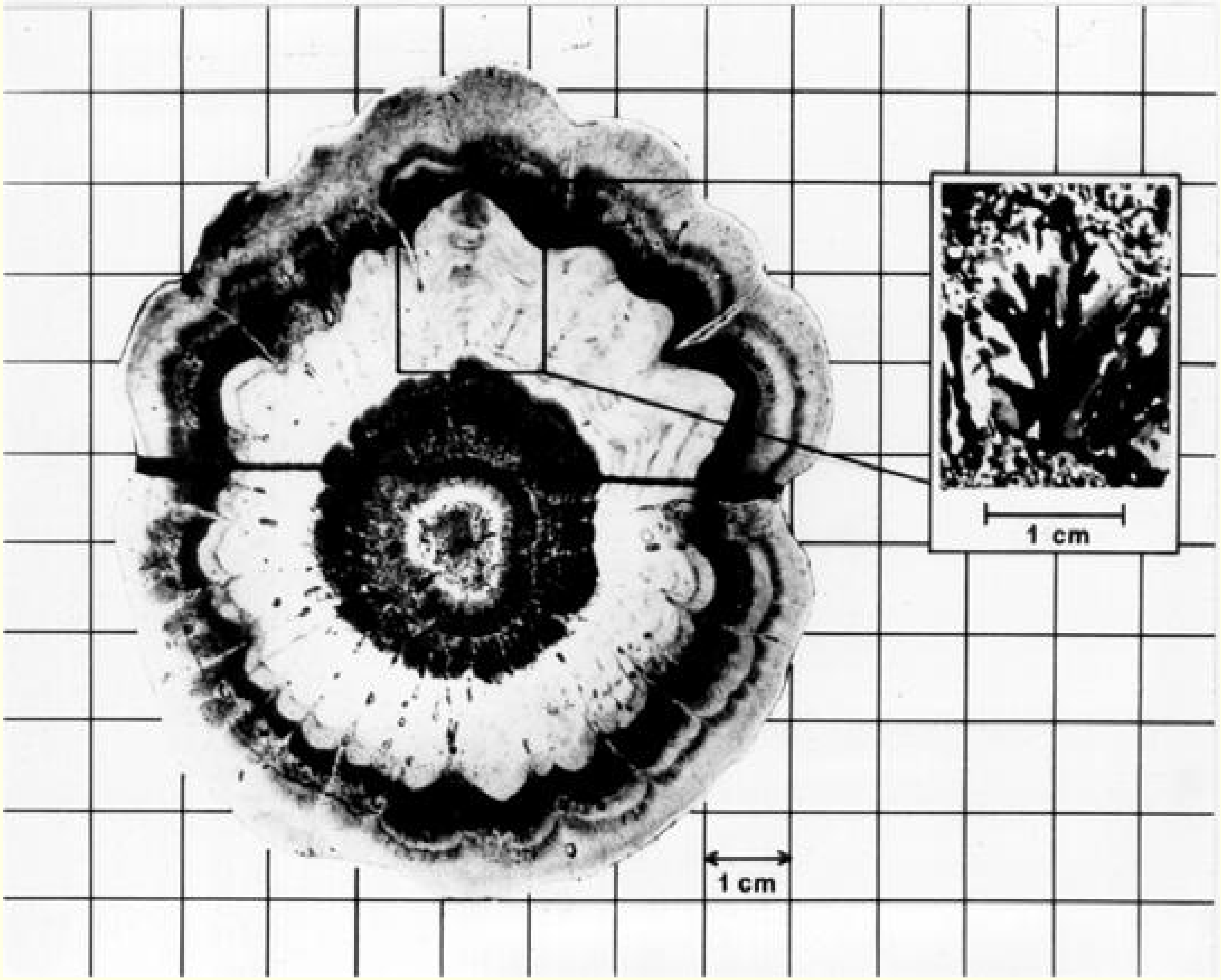
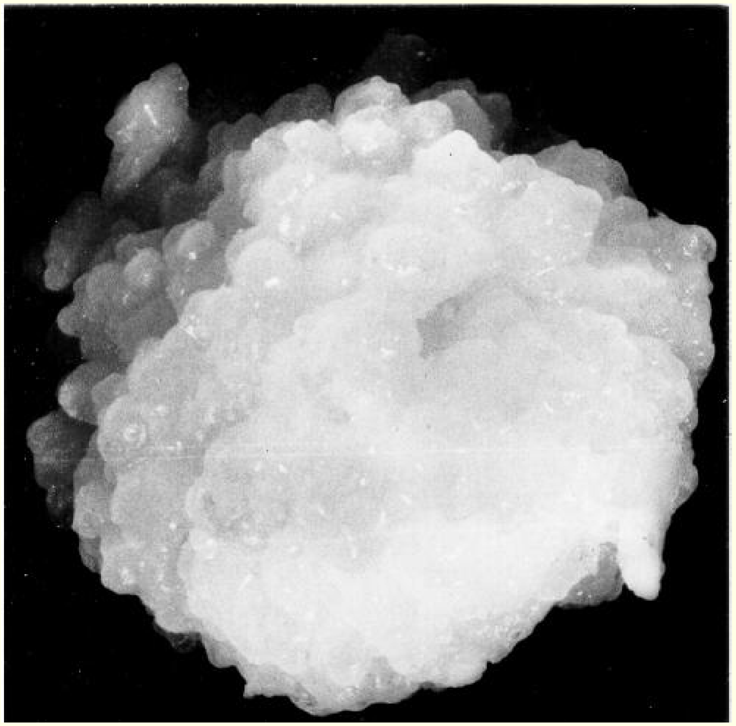
If a thin section is cut from a hailstone and viewed in transmitted light, it is often seen to consist of alternate dark and light layers (Figure follows).

The dark layers are opaque ice containing numerous small air bubbles, and the light layers are clear ice. Clear ice is more likely to form when the hailstone is growing wet.



Thin section through the center of a hailstone.

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.



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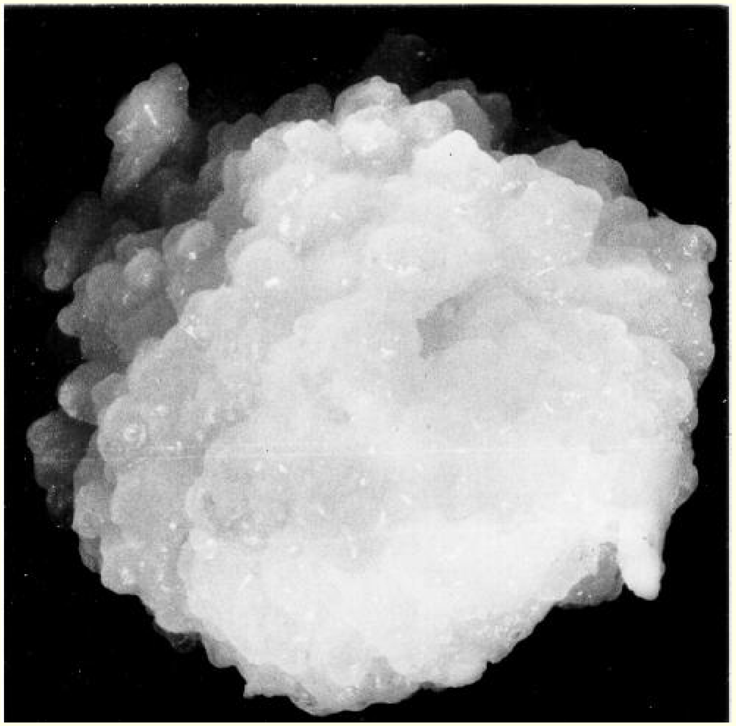

The development of lobes in a hailstone may be due to the fact that small bumps on a hailstone will be areas of enhanced collection efficiencies for droplets.

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For example, graupel particles 1 and 4 mm in diameter have terminal fall speeds of about 1 and 2.5 $\mathrm{m\,s^{-1}}$ respectively.

Consequently, the frequency of collisions of ice particles in clouds is greatly enhanced if some riming has taken place.

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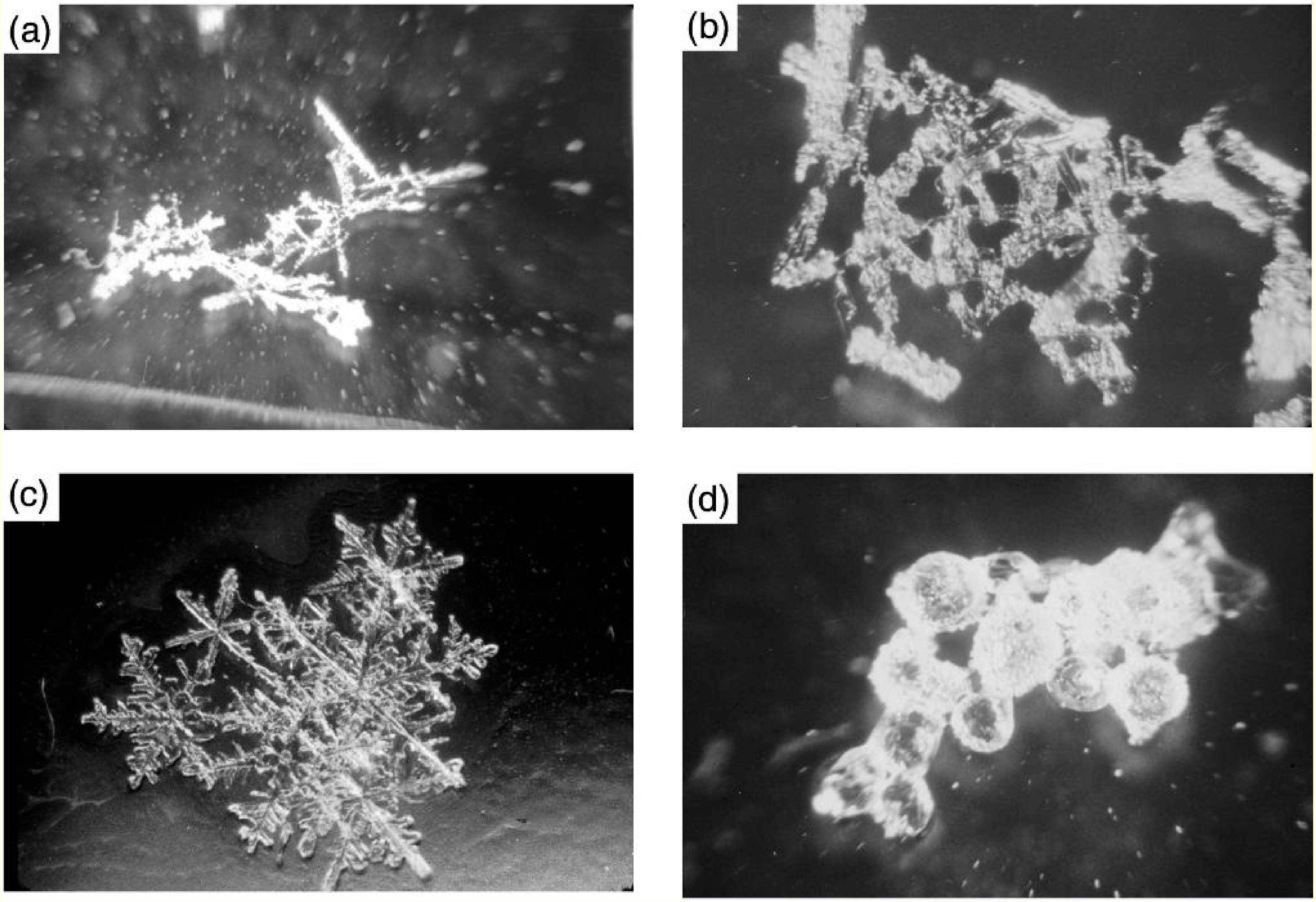
Some examples of ice particle aggregates are shown below.



Aggregates of (a) rimed needles; (b) rimed columns; (c) dendrites; (d) rimed frozen drops.

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Since Findeisen carried out his field studies in northwestern Europe, he was led to believe that all rain originates as ice. However, as we have seen , rain can also form in warm clouds by the collision-coalescence mechanism.

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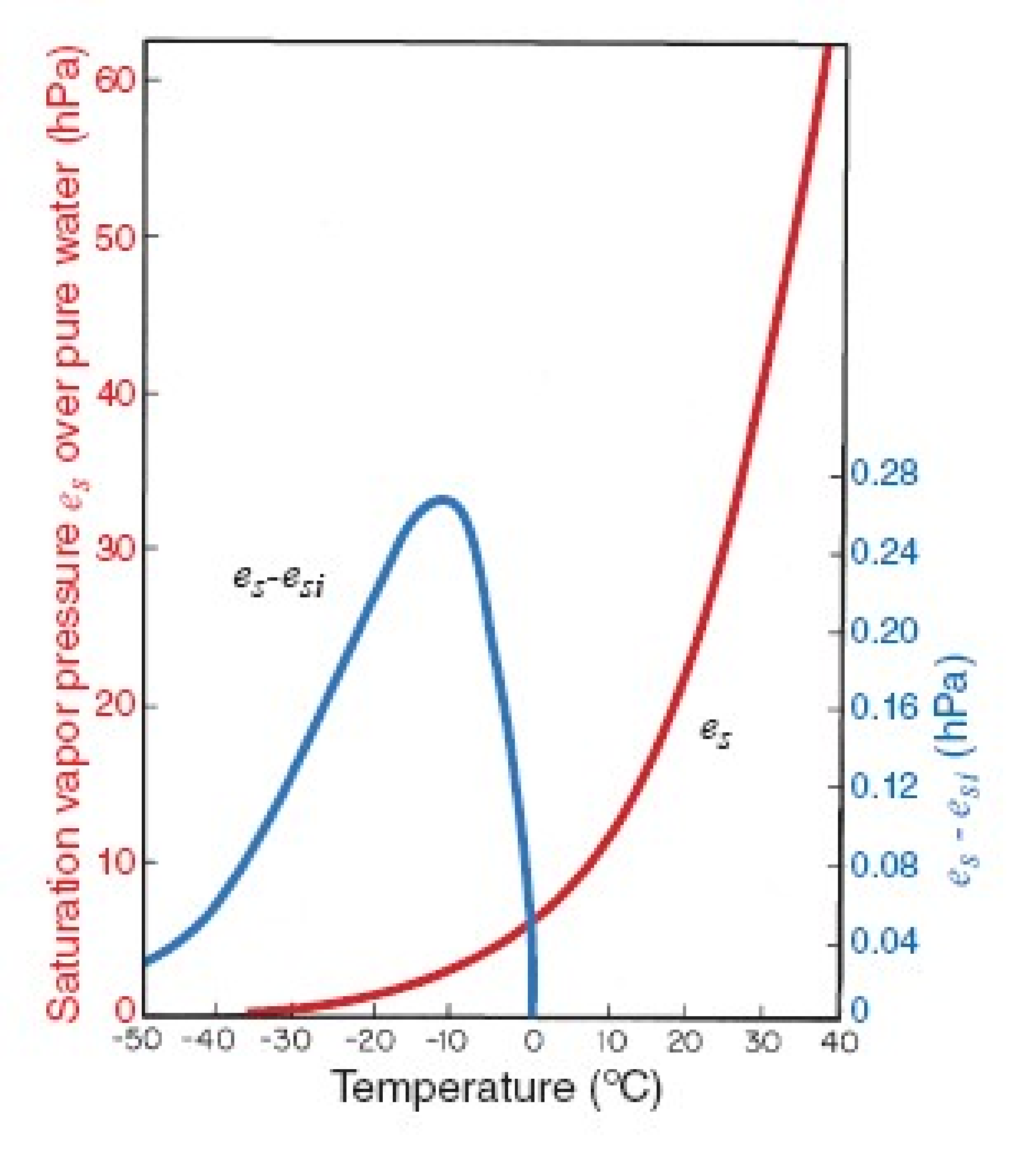
We conclude from these calculations that the growth of ice crystals, first by deposition from the vapour phase in mixed clouds and then by riming and/or aggregation, can produce precipitation-sized particles in about 30 minutes.

Bergeron-Findeisen Process



Saturation vapour pressure over water (Red) and the difference between the saturation pressures over water and over ice (Blue).

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This Bergeron-Findeisen Process results in rapid growth of ice crystals and therefore enales precipitation in cold clouds.

Radar Bright Band

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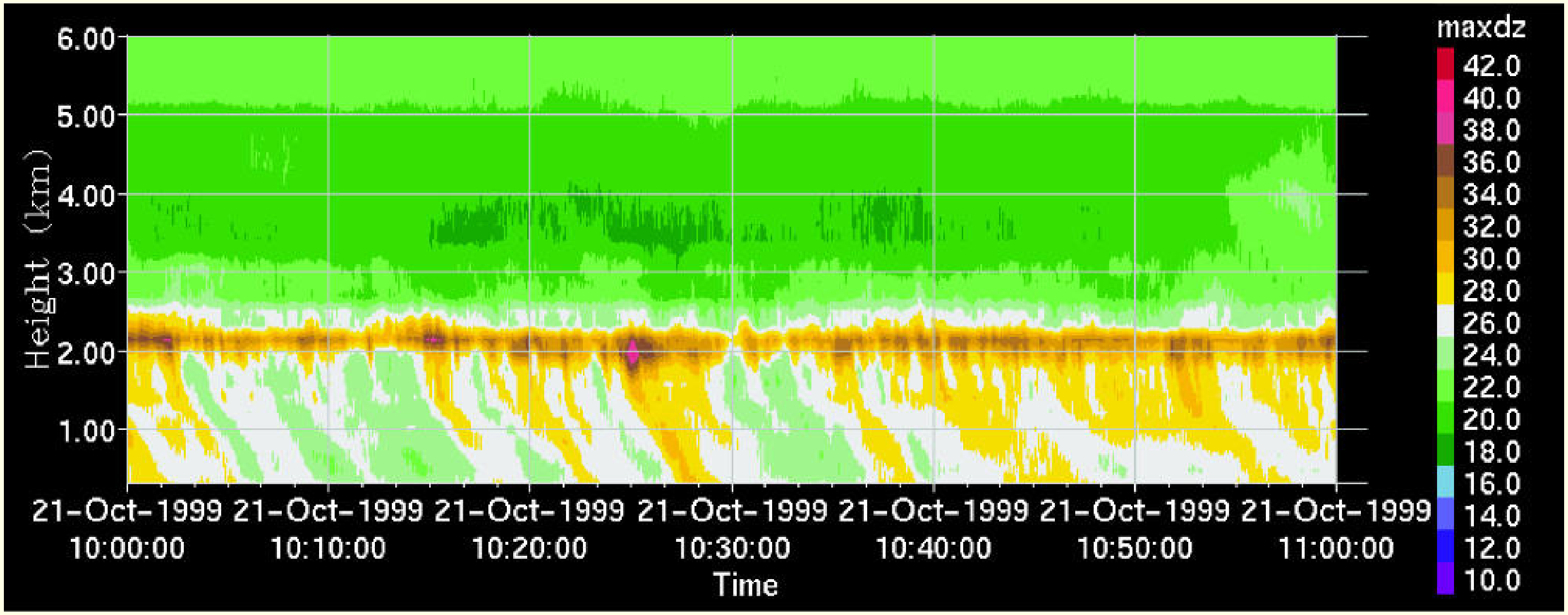

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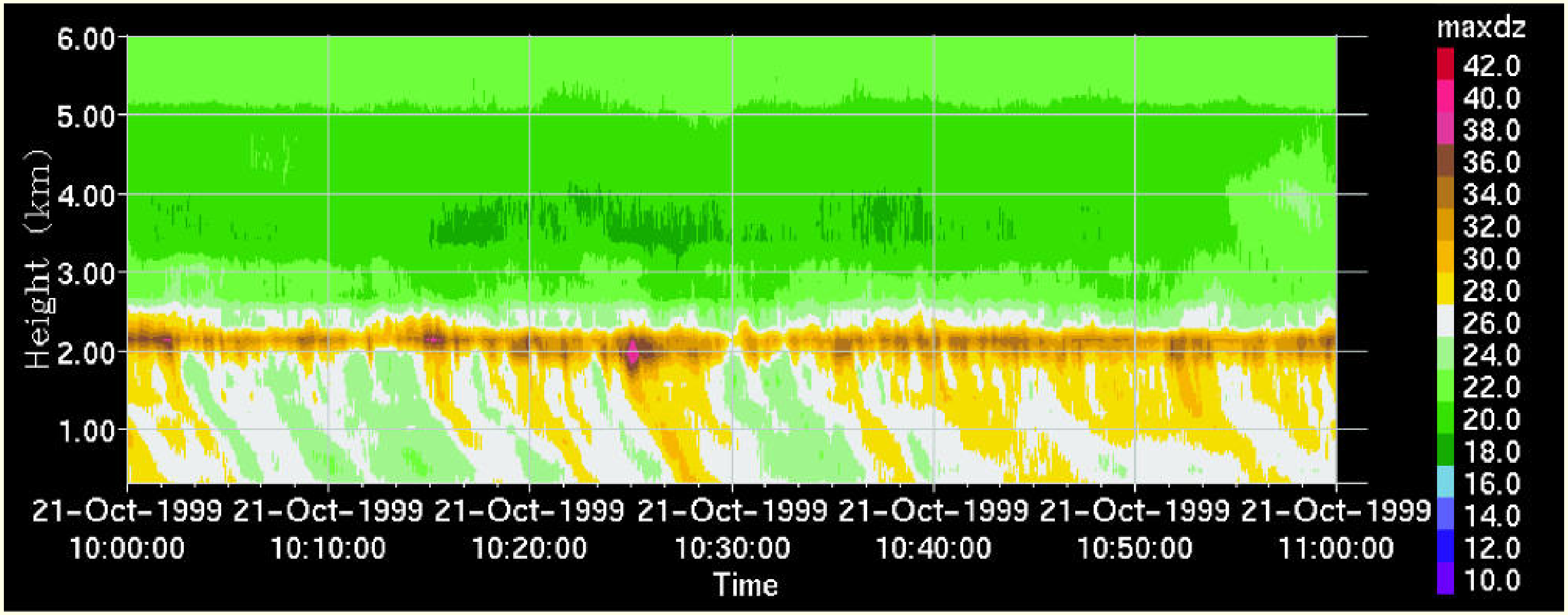
The role of the ice phase in producing precipitation in cold clouds is demonstrated by radar observations.

Shown here is a radar image, with the radar antenna pointing vertically upward.



The horizontal band (brown) just above a height of 2 km was produced by the melting of ice particles. This is referred to as the "bright band".

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When the crystals have melted completely they collapse into droplets, and their terminal fall speeds increase so that the concentration of particles is reduced. These changes result in a sharp decrease in radar reflectivity below the melting band.

The sharp increase in particle fall speeds produced by melting is illustrated below, showing the spectrum of fall speeds of precipitation particles measured at various heights with a vertically pointing Doppler radar.

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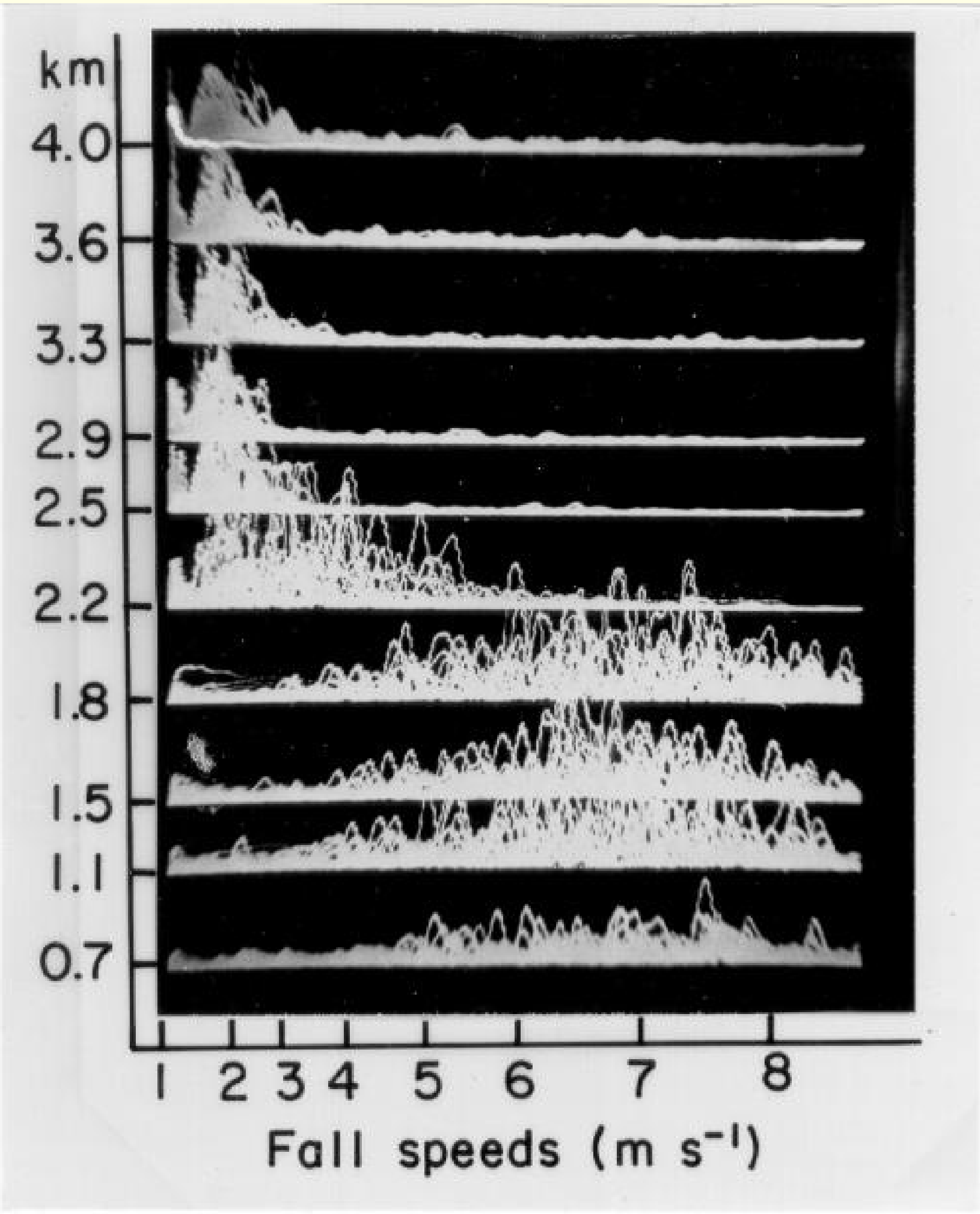
At heights above 2.2 km the particles are ice with fall speeds centered around 2 m s^{-1}. At 2.2 km the particles are partially melted, and below 2.2 km there are raindrops with fall speeds centered around 7 m s^{-1}.



Spectra of Doppler fall speeds for precipitation particles at ten heights in the atmosphere. The melting level is at about 2.2 km.

Classification of Solid Precipitation

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1. ***A plate*** **is a thin, platelike 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.**

2. ***A stellar crystal*** **is a thin, flat snow crystal in the form of a conventional star. It generally has six arms but stellar crystals with three or twelve 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.**

3. 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.**

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5. ***A spatial dendrite*** **is a complex snow crystal with fern-like arms which 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.**

6. ***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.**

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7. ***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.**

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8. ***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 which is approximately spherical.**

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10. *A hailstone* 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 which accompany thunderstorms.