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MANUAL FOR SNOWFLAKE OBSERVATION, IDENTIFICATION, AND REPLICATION

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by

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Department of Atmospheric Science, Colorado State University

Oh! the snow, the beautiful snow,
Filling the sky and the earth below;...
Beautiful snow, from the heavens above
Pure as an angel and fickle as love!

John Whitaker Watson

When you start looking closely at snowflakes, you'll see that they come in many very different shapes. For example, some will be flat, perfectly six-sided plates while others will have intricate fernlike crystalline arms growing out every which way.

What shape a snow crystal grows in depends primarily on the temperature of the cloud where the crystal is growing and on how much water vapor is in the air. Therefore, we can learn quite a bit about a cloud simply by studying the snowflakes that fall from it.

Most of the snow crystals you'll see will fit neatly into one of the twelve catagories described on the following five pages and on page 13. The magnification of the photographs of snow crystals reproduced on these pages varies considerably, so the size of the illustration does not reflect the relative size of the snow crystal.

HEXAGONAL PLATES

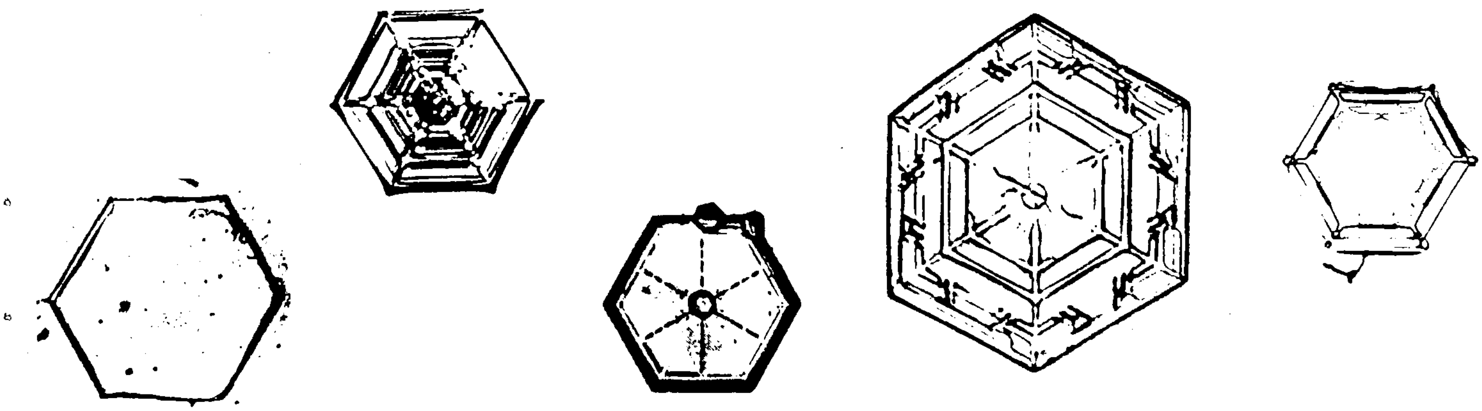


Fig. 1. Depictions of hexagonal plates. (Taken from Hardy et al., 1982; Nakaya, 1954; Pruppacher and Klett, 1978; Wallace, 1977.)

Hexagonal plates are thin, platelike snow crystals the form of which more or less resembles a hexagon or in rare cases, a triangle. Generally all edges or alternate edges of the plate are similar in pattern and length. Hexagonal plates, sometimes simply called plates, may be solid with no internal markings or semisolid containing internal structure due to air inclusions.

STELLAR CRYSTALS

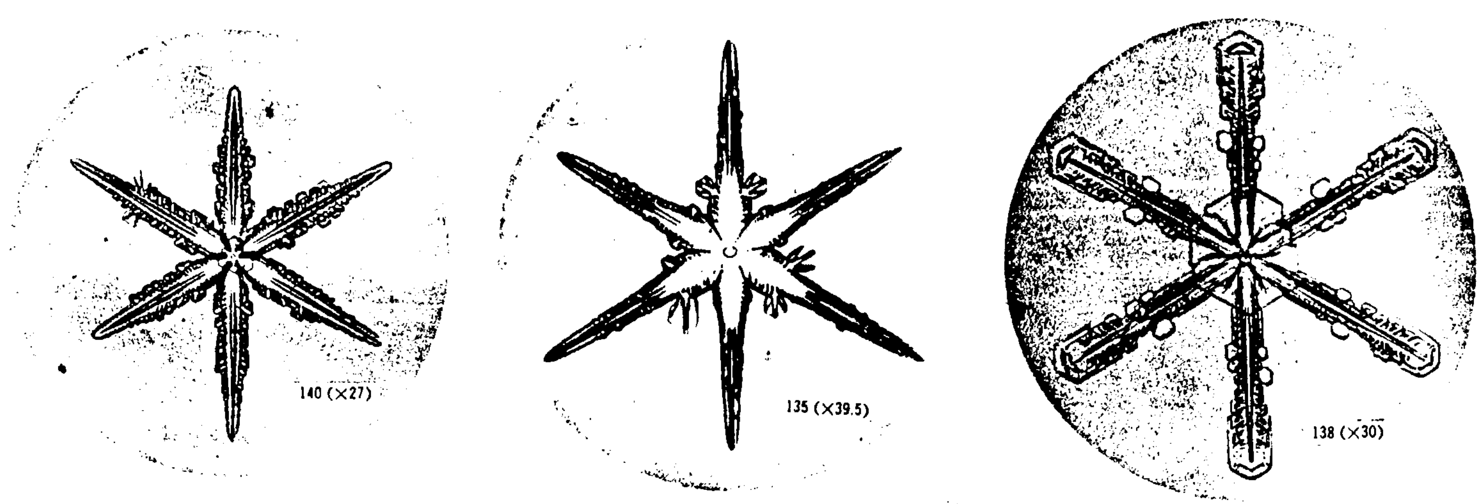


Fig. 2. Depictions of stellar crystals. (Taken from Nakaya, 1954.)

Stellar crystals are thin, flat snow crystals with six arms forming the shape of a star. Occasionally stellars with 3 or 12 arms may be found. These 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.

DENDRITES

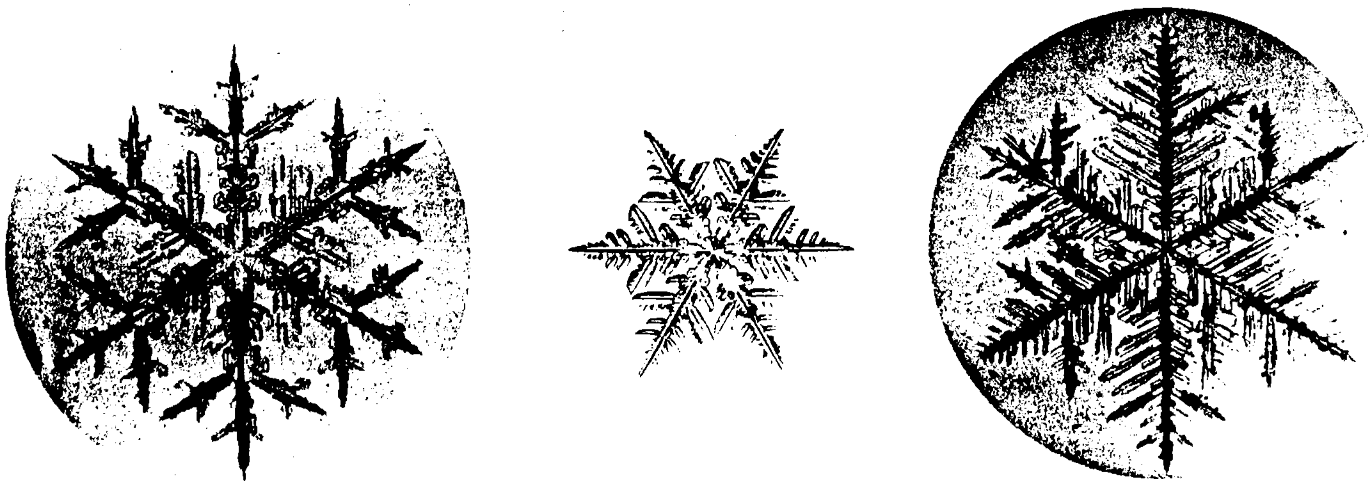


Fig. 3. Depictions of dendrites. (Taken from Nakaya, 1954; Hardy et al., 1982.)

Dendrites, also called plane dendrites, are special forms of stellar crystals in which the six arms have developed intricate fernlike structure.

SPACIAL DENDRITES

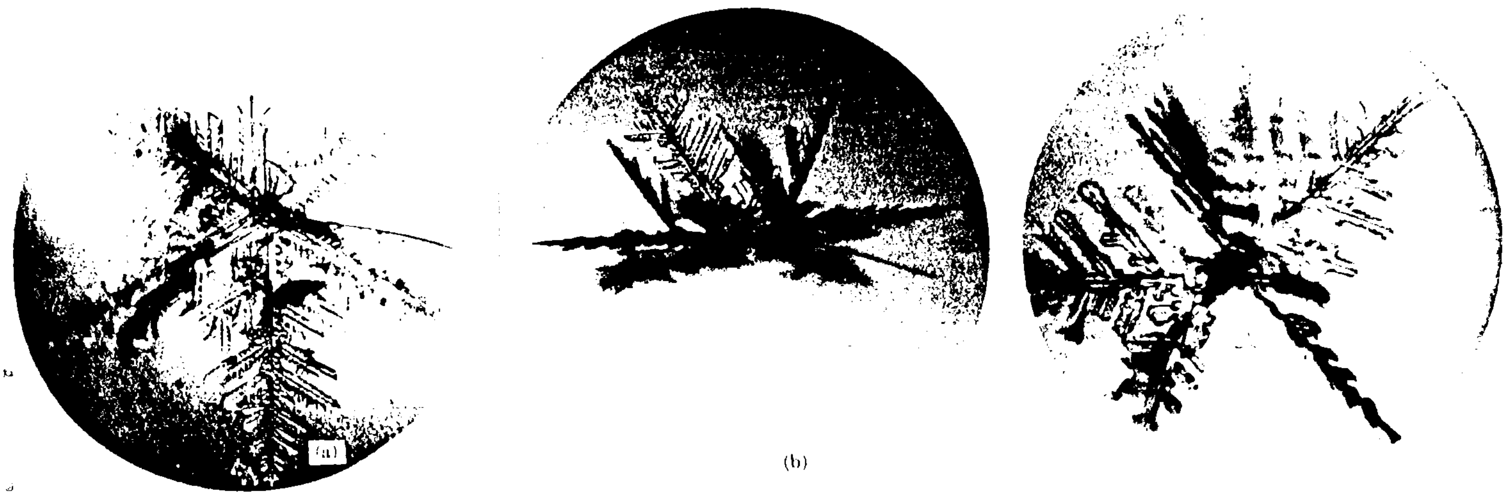


Fig. 4. Depictions of spacial dendrites. (Taken from Nakaya, 1954.)

Spacial dendrites are complex snow crystals with fernlike arms which do not lie in a plane or in parallel planes but extend in many directions from a central nucleus. They exhibit a roughly spherical symmetry.

COLUMNS

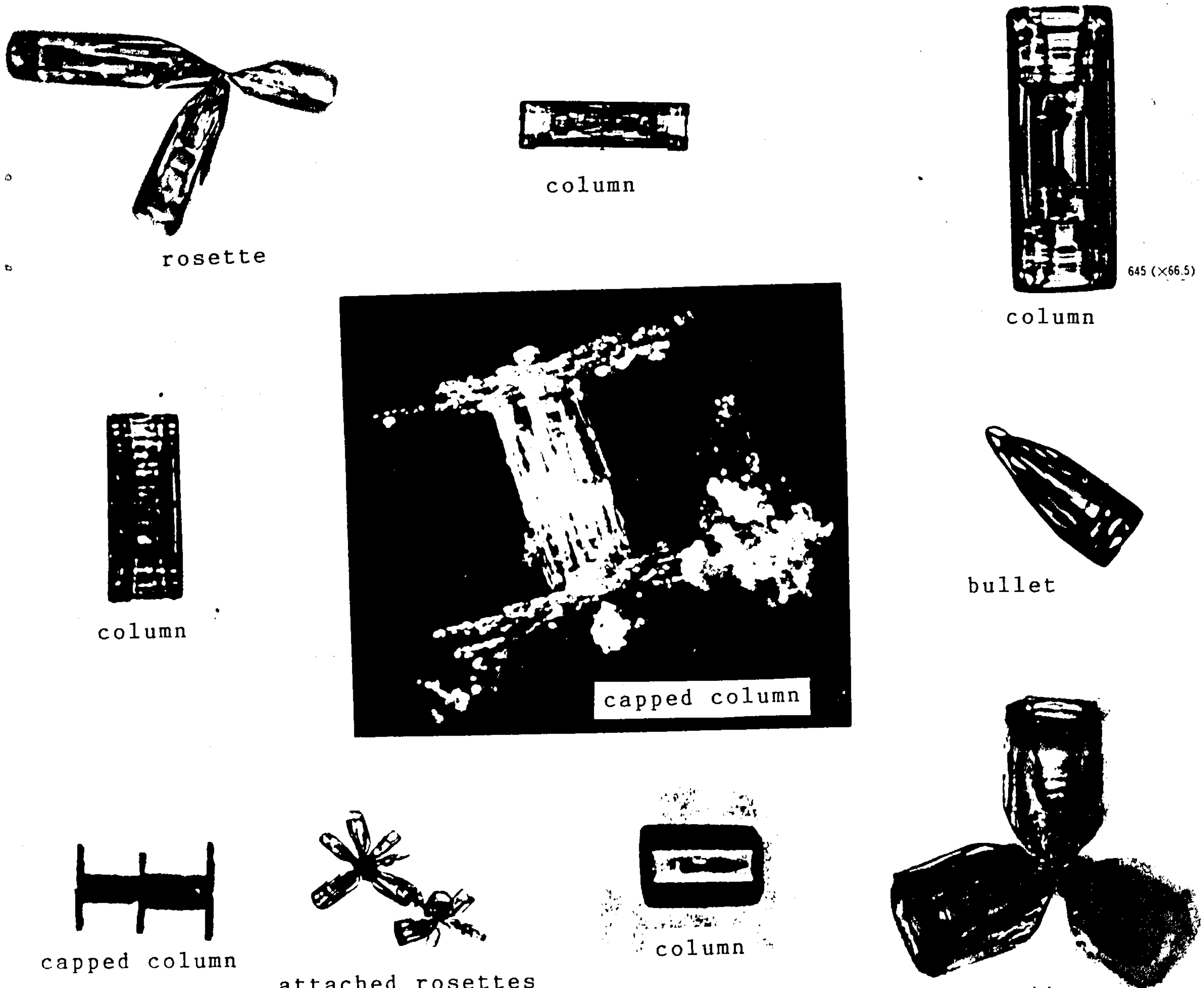


Fig. 5. Depictions of columnar crystals. (Taken from Hardy et al., 1982; LaChapelle, 1969; Nakaya, 1954; Pruppacher and Klett, 1978; Wallace and Hobbs, 1977.)

Columnar crystals are relatively short, six sided columns. They are either solid or hollow. The ends of a column are generally flat, but some may have a pyramid on one end. Columns with pyramids on an end (called bullets) may be attached at the pointed end to other columns and are called rosettes. There are three main types of columns:

Solid columns
Hollow columns
Capped columns

Capped columns have hexagonal plates or stellar crystals on at least one end.

SECTOR PLATES

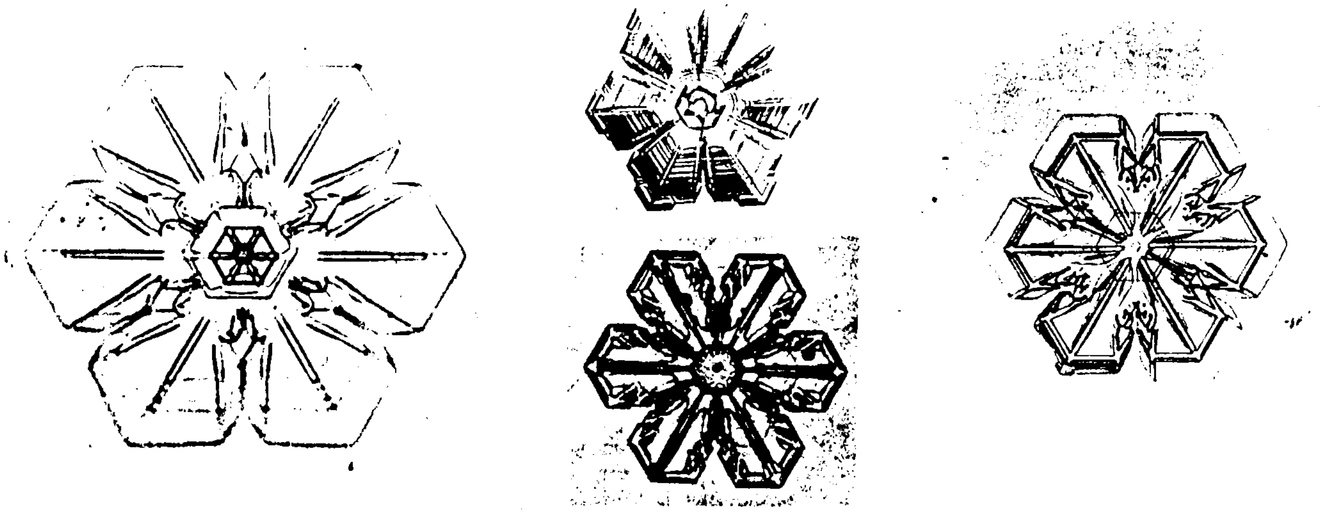


Fig. 6. Depictions of sector plates. (Taken from Hardy et al., 1982; Nakaya, 1954; Pruppacher and Klett, 1978.)

Sector plates are thin, platelike crystals with plates growing in six radiating sectors or sections. They appear as if each arm of a stellar grew out to form a section of plate.

NEEDLES

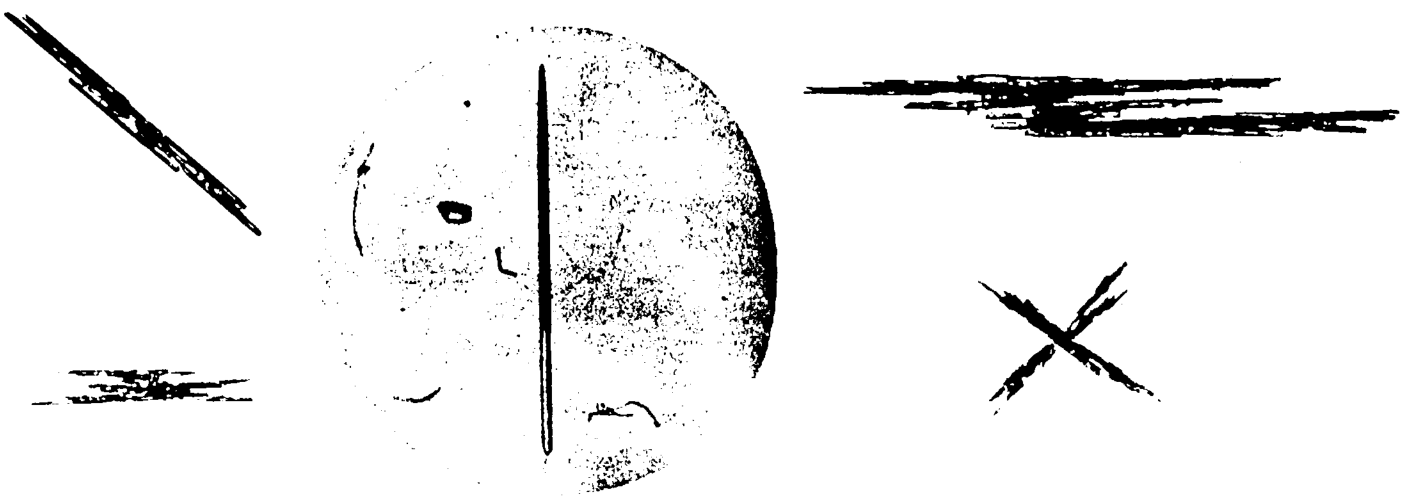


Fig. 7. Depictions of needles. (Taken from Nakaya, 1954; Pruppacher and Klett, 1978; Hardy et al., 1982.)

Needles are very slender, needlelike snow particles of approximately cylindrical form. This class includes hollow bundles of parallel needles and combinations of needles arranged in any of a wide variety of fashions.

SHEATHS

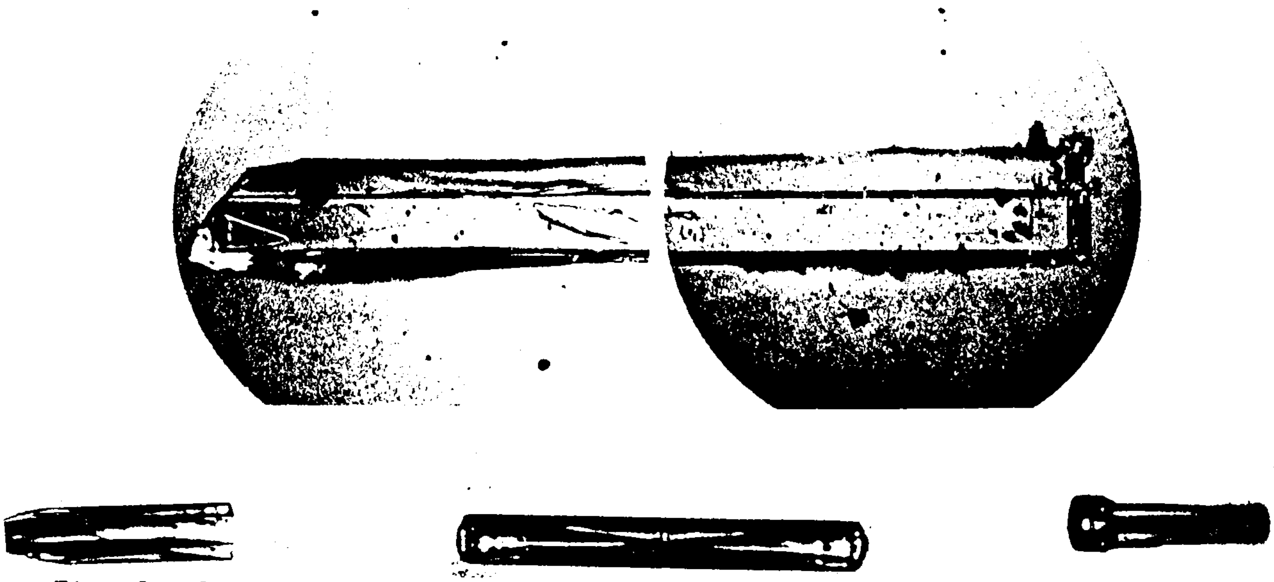


Fig. 8. Depictions of sheaths. (Taken from Nakaya, 1954; Pruppacher and Klett, 1978.)

Sheaths are a type of needle which, as the name implies, are hollow. These are extremely thin, hollow columns.

IRREGULAR CRYSTALS

Fig. 9. Depictions of irregular crystals. (Taken from Nakaya, 1954.)

Irregular crystals are snow particles 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.

You will be able to classify almost all the snow crystals you'll see as one of the eleven types of snow crystals just described or as graupel, which is described on page 13 in the section on riming:

Hexagonal plates
Stellar crystals
Dendrites
Spacial dendrites
Solid columns
Hollow columns
Capped columns
Sector plates
Needles
Sheaths
Irregular crystals
Graupel

Occasionally though, you may come across a crystal that defies these major groupings or you may want to define the snow crystal more precisely. In these cases, you should refer to the following Meteorological Classification of Snow Crystals by Choji Magono and C. W. Lee. Just follow down the outline to the crystal description that seems best. Then use the outline headings (for example, N 1 d refers to a bundle of elementary sheaths) to guide you to the correct sketch of the crystal on the two pages following the outline.

(N) Needle crystal
- 1. Simple needle
  - a. Elementary needle
  - b. Bundle of elementary needles
  - c. Elementary sheath
  - d. Bundle of elementary sheaths
  - e. Long solid column
- 2. Combination of needle crystals
  - a. Combination of needles
  - b. Combination of sheaths
  - c. Combination of long solid columns

(C) Columnar crystal
- 1. Simple column
  - a. Pyramid
  - b. Cup
  - c. Solid bullet
  - d. Hollow bullet
  - e. Solid column
  - f. Hollow column
  - g. Solid thick plate
  - h. Thick plate of skeleton form
  - i. Scroll

2. Combination of columns
   a. Combination of bullets
   b. Combination of columns

(P) Plane crystal
1. Regular crystal developed in one plane
   a. Hexagonal plate
   b. Crystal with sectorlike branches
   c. Crystal with broad branches
   d. Stellar crystal
   e. Ordinary dendrite crystal
   f. Fernlike crystal
2. Plane crystal with extensions of different form
   a. Stellar crystal with plates at ends
   b. Stellar crystal with sectorlike ends
   c. Dendritic crystal with plates at ends
   d. Dendritic crystal with sectorlike ends
   e. Plate with simple extensions
   f. Plate with sectorlike extensions
   g. Plate with dendritic extensions
3. Crystal with irregular number of branches
   a. Two-branched crystal
   b. Three-branched crystal
   c. Four-branched crystal
4. Crystal with 12 branches
   a. Broad branch crystal with 12 branches
   b. Dendritic crystal with 12 branches
5. Malformed crystal
   Many varieties
6. Spatial assemblage of plane branches
   a. Plate with spatial plates
   b. Plate with spatial dendrites
   c. Stellar crystal with spatial plates
   d. Stellar crystal with spatial dendrites
7. Radiating assemblage of plane branches
   a. Radiating assemblage of plates
   b. Radiating assemblage of dendrites

(CP) Combination of column and plane crystals
1. Column with plane crystals at both ends
   a. Column with plates
   b. Column with dendrites
   c. Multiple capped column
2. Bullet with plane crystals
   a. Bullet with plates
   b. Bullet with dendrites
3. Plane crystal with spatial extensions at ends
   a. Stellar crystal with needles
   b. Stellar crystal with columns
   c. Stellar crystal with scrolls at ends
   d. Plate with scrolls at ends

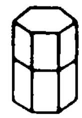
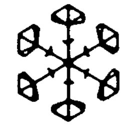
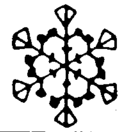
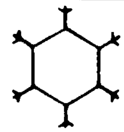
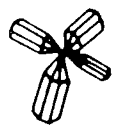
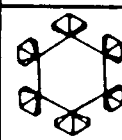
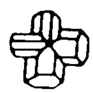
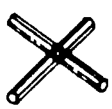
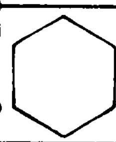
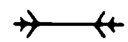
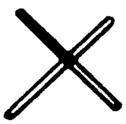
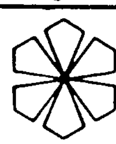
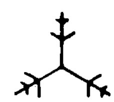
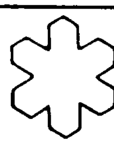
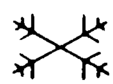
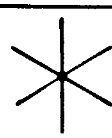
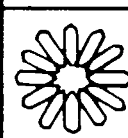
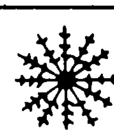
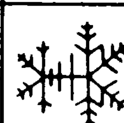
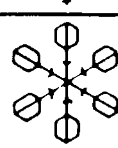
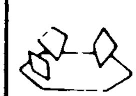
(S) Columnar crystal with extended side planes
1. Side planes
2. Scalelike side planes
3. Combination of side planes, bullets and columns

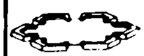
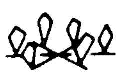
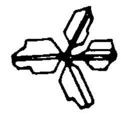
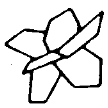
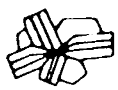
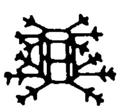
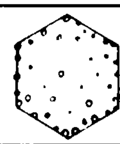
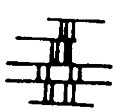
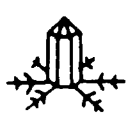
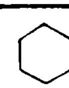
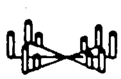
(R) Rimed crystal (Crystal with cloud droplets attached)
1. Rimed crystal
   a. Rimed needle crystal
   b. Rimed columnar crystal
   c. Rimed plate or sector
   d. Rimed stellar crystal
2. Densely rimed crystal
   a. Densely rimed plate or sector
   b. Densely rimed stellar crystal
   c. Stellar crystal with rimed spatial branches
3. Graupellike snow
   a. Graupellike snow of hexagonal type
   b. Graupellike snow of lump type
   c. Graupellike snow with nonrimed extensions
4. Graupel
   a. Hexagonal graupel
   b. Lump graupel
   c. Conelike graupel

(I) Irregular snow crystal
1. Ice particle
2. Rimed particle
3. Broken piece from a crystal
   a. Broken branch
   b. Rimed broken branch
4. Miscellaneous

(G) Germ of snow crystal (ice crystal)
1. Minute column
2. Germ of skeleton form
3. Minute hexagonal plate
4. Minute stellar crystal
5. Minute assemblage of plates
6. Irregular germ

Table 1. The Magono-Lee Classification of Natural Snow Crystals. (Taken from Magono and Lee, 1966.)

	N1a Elementary needle		C1f Hollow column		P2b Stellar crystal with sectorlike ends
	N1b Bundle of elementary needles		C1g Solid thick plate		P2c Dendritic crystal with plates at ends
	N1c Elementary sheath		C1h Thick plate of skeleton form		P2d Dendritic crystal with sectorlike ends
	N1d Bundle of elementary sheaths		C1i Scroll		P2e Plate with simple extensions
	N1e Long solid column		C2a Combination of bullets		P2f Plate with sectorlike extensions
	N2a Combination of needles		C2b Combination of columns		P2g Plate with dendritic extensions
	N2b Combination of sheaths		P1a Hexagonal plate		P3a Two-branched crystal
	N2c Combination of long solid columns		P1b Crystal with Sectorlike branches		P3b Three-branched crystal
	C1a Pyramid		P1c Crystal with broad branches		P3c Four-branched crystal
	C1b Cup		P1d Stellar crystal		P4a Broad branch crystal with 12 branches
	C1c Solid bullet		P1e Ordinary dendritic crystal		P4b Dendritic crystal with 12 branches
	C1d Hollow bullet		P1f Fernlike crystal		P5 Malformed crystal
	C1e Solid column		P2a Stellar crystal with plates at ends		P6a Plate with spatial plates

	P6b Plate with spatial dendrites		CP3d Plate with scrolls at ends		R3c Graupel-like snow with nonrimed extensions
	P6c Stellar crystal with spatial plates		S1 Side planes		R4a Hexagonal graupel
	P6d Stellar crystal with spatial dendrites		S2 Scalelike side planes		R4b Lump graupel
	P7a Radiating assemblage of plates		S3 Combination of side planes, bullets, and columns		R4c Conelike graupel
	P7b Radiating assemblage of dendrites		R1a Rimed needle crystal		I1 Ice particle
	CP1a Column with plates		R1b Rimed columnar crystal		I2 Rimed particle
	CP1b Column with dendrites		R1c Rimed plate or sector		I3a Broken branch
	CP1c Multiple capped column		R1d Rimed stellar crystal		I3b Rimed broken branch
	CP2a Bullet with plates		R2a Densely rimed plate or sector		I4 Miscellaneous
	CP2b Bullet with dendrites		R2b Densely rimed stellar crystal		G1 Minute column
					G2 Germ of skeleton form
	CP3a Stellar crystal with needles		R2c Stellar crystal with rimed spatial branches		G3 Minute hexagonal plate
	CP3b Stellar crystal with columns		R3a Graupel-like snow of hexagonal type		G4 Minute stellar crystal
					G5 Minute assemblage of plates
	CP3c Stellar crystal with scrolls at ends		R3b Graupel-like snow of lump type		G6 Irregular germ

Now that you can identify snow crystals, there are two more parameters for you to take into consideration: riming and aggregation.

Riming:

Many of the snow crystals you'll see will have grown in clouds with liquid water droplets. These cloud droplets may be many degrees colder than what is commonly considered the freezing temperature of water, yet they will still be liquid. If one of these supercooled droplets collides with a snow crystal (or other object) it will often freeze to it. This is called riming.

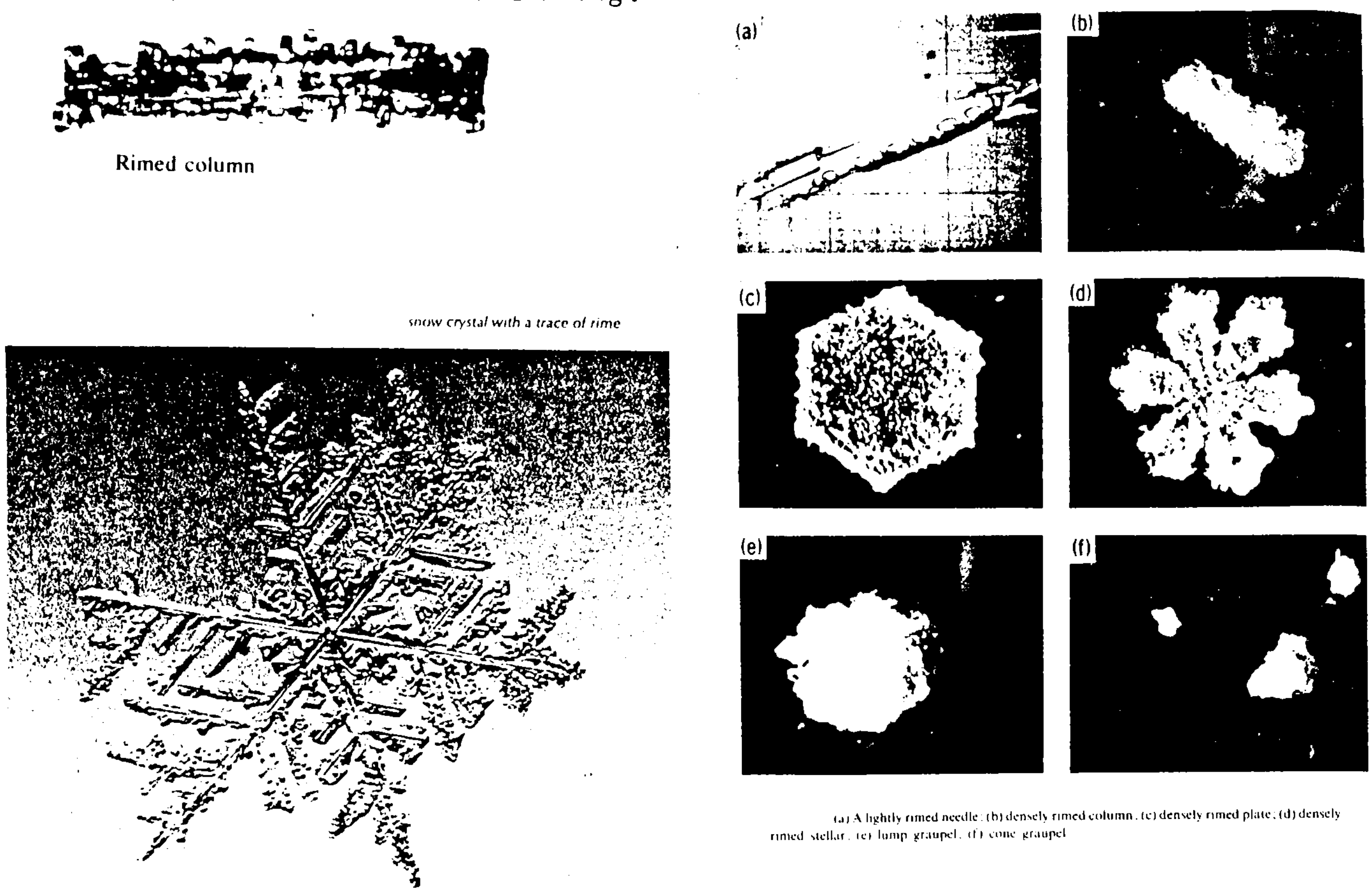


Fig. 10. Depictions of rimed snow crystals. (Taken from LaChapelle, 1969; Pruppacher and Klett, 1978; Wallace and Hobbs, 1977.)

When you are examining the snow crystals, you should evaluate how much riming has occurred on each type of snow crystal:

No riming: the pristine snow crystals show no little droplets frozen to them.

Light to moderate riming: the snow crystals are still clearly visible despite some frozen cloud droplets on them.

Heavy riming: the snow crystals are covered with frozen cloud droplets but they still have enough of their shape visible for you to identify which type of crystal they are.

Graupel: When riming proceeds beyond the point where you can no longer discern the shape of the ice crystal, the particle is referred to as graupel.

GRAUPEL

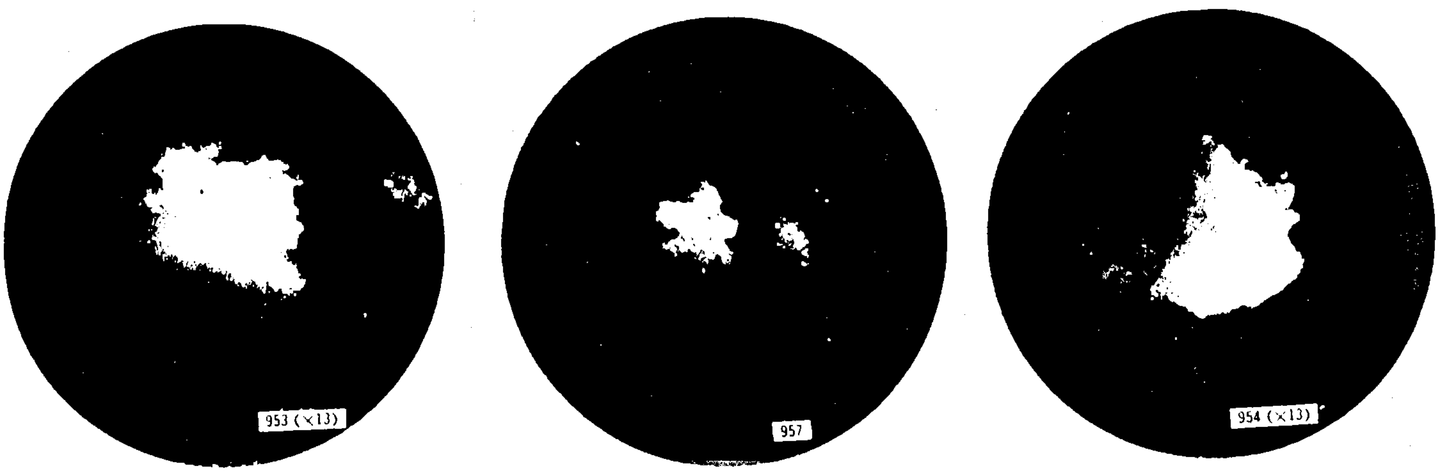


Fig. 11. Depictions of graupel. (Taken from Nakaya, 1954.)

Graupel, which includes soft hail, small hail, and snow pellets, is a snow crystal or particle coated with a very heavy deposit of rime. It may retain some evidence of the outline of the original crystal but not enough to be able to identify which crystal type it was. The most common type of graupel has a form which is approximately spherical. Another common form is conical in shape.

Aggregation:

Snow crystals that collide and get stuck together form larger snowflakes called aggregates. How efficiently the aggregation of snow crystals into large snowflakes occurs depends on both the type of crystal and the temperature. So determining the amount of aggregation and the type of snow crystals involved can also tell us a lot about the cloud and the air below the cloud.

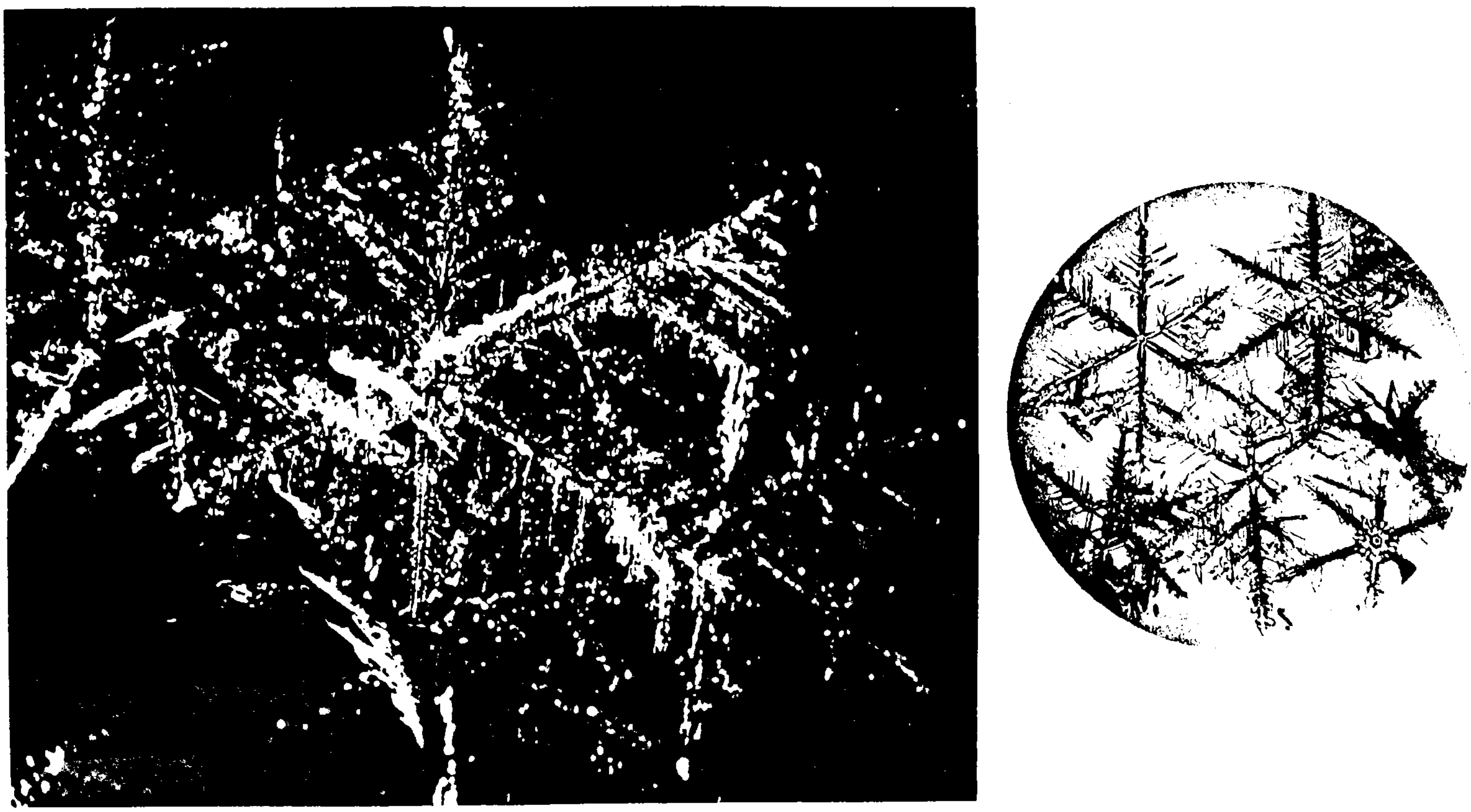


Fig. 12. Depictions of aggregates. (Taken from LaChapelle, 1969; Nakaya, 1954.)

When you look at your collection of snowflakes, see how many of the snowflakes are aggregates made up of two or three snow crystals, called simple aggregates, and how many are aggregates made up of four or more snow crystals, called mature aggregates. Look closely at the aggregates to determine which types of crystals are in the aggregate and count or estimate how many of each type are in the aggregate.

Techniques for Observing Snowflakes

Just using your naked eyes, you can examine snowflakes that land on the sleeve of your coat. But a more careful and systematic approach can give better results.

The material of choice for collecting snowflakes is black velvet. The dark color gives a good contrast for clearly seeing the white or glossy clear flakes. Also the soft velvet surface minimizes breakage and holds the delicate snowflakes partially in the air for easier viewing. You will find, though, that many other materials such as flannel or even dark cardboard work fine. 250 square centimeters ($6\frac{1}{4}$ inches by $6\frac{1}{4}$ inches) is a convenient size for the material. And you can just set it on a plate to keep it flat.

A hand held magnifying glass is a definite improvement over the naked eye for examining the intricate structure of snow crystals.

Direct Observation of Frozen Precipitation

Materials required:

- Sampling plate with an area of about 250 cm^2 covered by black velvet or similar material.
- Magnifying glass.
- Thermometer.
- Stopwatch.
- Ruler for measuring crystals.

Procedure:

1) Cool the sampling surface:

The sampling surface must be cold or the snowflakes will start melting as soon as they land. The easiest way to cool the sampling surface is by setting it outside in a sheltered area or in a bag for a few minutes before you start collecting snow crystals. Shake off any flakes that landed on your surface before you start sampling.

2) Collect snowflakes:

Hold the sampling surface face up in the falling snow for 1 to 15 seconds or perhaps longer depending on the intensity of the snowfall. Then move it to a sheltered area such as under the eaves or downwind side of a building.

3) Examine the individual crystals:

See what types of snow crystals are present and count and record the number of each type. If there is a huge number of crystals, count the crystals in a small area and estimate for the entire surface. For each type of crystal present, measure several of the crystals and estimate the average diameter of that type of crystal (with needle type crystals, measure the length instead of diameter). Also, record how large the largest crystal of that type is and what size seems to be the most common (this is called the mode size) for that type of crystal. And finally, record how much riming was present on each type of crystal.

4) Examine the aggregates:

Count and record the number of simple aggregates made up of 2 or 3 snow crystals and the number of mature aggregates made up of 4 or more crystals. With each group of aggregates, record what type of crystals are in them and the average diameter of that type of aggregate. For mature aggregates, estimate the average number of crystals per aggregate. Comment on the amount of riming on the aggregates.

5) Record the weather conditions:

The weather conditions that should be recorded include the air temperature, the winds (calm, light, strong), and the height of the cloud base and cloud top. Accurately estimating the height of the bottom of a cloud takes practice, but even a rough estimate is helpful. In mountainous areas, you can sometimes look across a valley and estimate how high up a nearby mountain you can see before your view is blocked by the cloud base. If you can't even see the cloud top, you can't estimate its height without data from another source.

6) Complete the records for the observation:

Be sure to record the date, location, time, and how long the sample was exposed to falling snow.

SAMPLE

SNOWFLAKE OBSERVATION RECORDS

SAMPLE

Date 1-15-87 Location Fort Collins Altitude 5080 ft Observer Peterson

Sampling time .... Winds	Exposure time .... Cloud base height	Air T°C ...... Cloud top height	Number	Average size	Mode size	Max size	Type of individual crystal or type (simple or mature) of aggregate, and amount of riming. Also, description of types of crystals in aggregates including estimate of the average number of each type of crystal.
9 AM	4 sec	-11°C	200	1 mm	1	1.5	Spacial dendrites - No riming.
—	—	—	15	1.5 mm	1.5	1.5	Sector plates - No riming.
light	200 m	?	3	3.5 mm	3	4.5	Mature aggregates - Average 8 spacial dendrites and no other crystals - No riming.

For more detailed studies, the crystals should be observed under a microscope, using either transmitted, reflected, or oblique illumination. Transmitted illumination highlights the boundary and internal structure of a crystal, but it gives rather poor contrast if the crystal is thin. Reflected illumination, which gives a white image against a dark background, reveals the surface structure. Oblique illumination can combine the advantages of both transmitted and reflected illumination if careful adjustments are made.

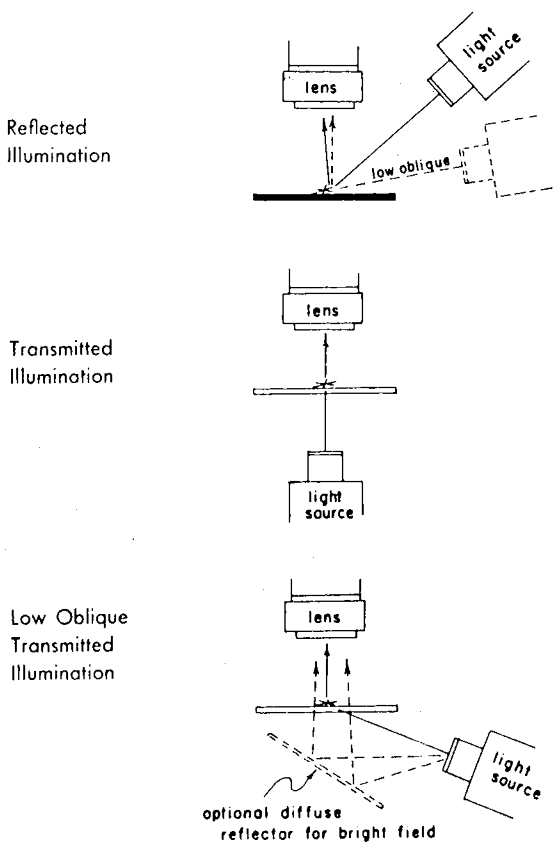


Fig. 13. Methods of illuminating snow crystals for photography. (From LaChapelle, 1969.)

Individual snow crystals may be easily collected at ground level when the air temperature is below about -5°C. At temperatures between 0 and -5°C it is generally necessary to cool the snow crystals before observing them under a microscope or the light you use to illuminate them will melt the crystals too rapidly.

Aggregates, especially large aggregates, can be difficult to properly collect because they are so fragile. One way to get un-deformed aggregate samples is to use a very special collecting surface: a spider web.

To make the web, first make a square wire frame enclosing about 15 cm^2. Next, catch a spider. You've probably noticed spiders dangling down on a line of spider silk before. Well, this is what you let your spider do. And as it lowers itself to the floor trying to escape, you rotate your frame so you appear to be reeling up the spider as you wrap the spider silk around the frame until you have enough strands of silk going across the frame to gently hold an aggregate.

Now you are ready to go outside and carefully catch a falling aggregate manually with your spider network. Once you have an un-deformed aggregate, you can measure its size, take a photograph, count the number of snow crystals of each type contained in the aggregate, and evaluate the amount of riming. Finally, you should measure the diameter of the drop the aggregate makes when it melts and use this information to calculate the bulk density of the aggregate. This process may be repeated until a satisfactory number of aggregates have been obtained.

Special Photographic Techniques for Snowflake Observation

Photographing Free Falling Snowflakes

To photograph free falling snowflakes you can use either a video camera or a still camera with a strobe flash. Choose a lens that will give the largest possible image of the snowflake. Another piece of equipment you'll find helpful, in addition to a tripod, is a precipitating tube to funnel the falling snowflakes into the region that is in focus.

Shadowphotographing Snow Crystals

The shadowphotograph method was first described by Higuchi (1956) and later adapted by Feng and Rauber (1986) for use with Polaroid 9 by 12 cm Type 52 Land film. The apparatus is very simple and is convenient for field work. As shown in the illustration, a piece of plexiglass (G) with a surface of 11 by 14 cm and a small flashlight bulb (L) are set apart at a distance of about 21 cm in a portable dark box (B). The top of the box is designed to accept a Polaroid Land film cartridge (C). The light (L) is lit by a battery (A). Several plexiglass plates are prepared by treating the surface of each plate with silicone oil (D.C. 200) so it will repel water.

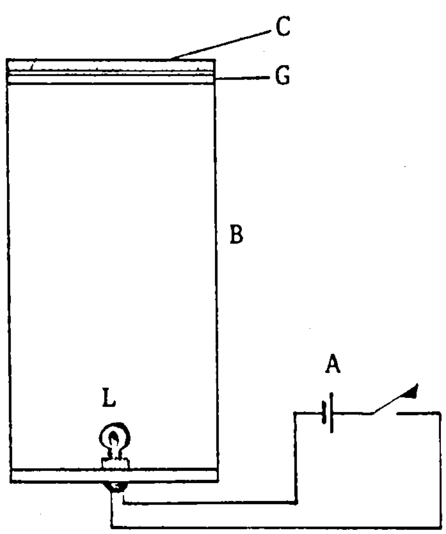


Fig. 14. Shadow photographing apparatus developed by Daxiong Feng, Colorado State University.

The procedure for recording the size and shape of snow crystals is as follows: The apparatus and plexiglass plates are cooled to the outdoor temperature. The collection area of a plexiglass plate is exposed to falling snow for a specific time and then moved under cover. The time of exposure is recorded as well as factors, such as wind, that may have influenced the collection of snow crystals. The film cartridge is then placed on the box above the plexiglass plate with snow crystals on it and exposed to the light source at the bottom of the box for a few seconds. This produces shadows of the crystals on the photographic film.

Since the distance between the snow crystals and the film is small compared to the distance to the light, the shadow image on the film is nearly full size and very clearly shows the outline of the crystals. These shadowphotographs capture the shape, size, and aggregation characteristics of the precipitation particles. One of the advantages of shadowphotographs is that this information can be obtained on a large number of particles at one time and each individual particle can be classified later.

The other major advantage of this technique is that you can calculate the bulk density of the snowflakes. To do this, you remove the plexiglass plate from the dark box and warm it slowly on a warm water bath. Due to capillary action and the water repelling nature of the oiled plexiglass surface, the individual crystals melt into hemispherical droplets. The plate is again placed in the dark box and a shadowphotograph of the droplets is taken by the same method. The volume of each droplet is calculated from the diameter of the image by assuming a hemispherical shape. From this information you can obtain the mass distribution and bulk densities of the snow crystals.

Careful checking of this technique has shown that the snow crystals are actually 2 percent smaller than the shadowphotograph image. To get the correct volume of the water droplets, assume a hemispherical shape but use a diameter 4 percent smaller than the shadowphotograph image.

Making Permanent Replicas of Snowflakes

You can make permanent replicas of snowflakes using clear fixative or clear lacquer. Fixatives, such as Krylon Crystal Clear Acrylic Spray Coating, are sold in art supply stores to spray on art work such as water-color paintings or charcoal drawings to keep them from smearing.

Procedure:

Cool the fixative and glass microscope slides by setting them outside for awhile so the snow crystals won't melt when they land.

Spray the fixative on one side of a dry slide and expose it to falling snow for one to ten seconds or more depending on the intensity of the snowfall.

When the snow crystals land, the fixative tends to creep over them, encasing them in a thin film. Depending on the snow crystals, temperature, and type of fixative, you may have better results if the snow crystals impact harder onto the fixative. If this is the case, hold the slide in your hand and swing it through the falling snow.

Place the slide in a sheltered, ventilated, and cold location while the fixative hardens.

The snow crystals will evaporate leaving a hollow cavity that is the replica. The best replicas result if the snow crystals are permitted to evaporate by sublimation, that is directly from ice to vapor with no liquid water stage. So the longer the sample is kept cold, the better.

Other materials have been used for snowflake replication with mixed results. New Skin, for example, makes great replicas when the slide is placed outside an airplane flying through a cloud, but does not seem to work very well with gently falling snow crystals at ground level.

Another product that has been widely used is Formvar, which is the trade name for polyvinyl formal. But, due to toxicology reasons, Monsanto, the only U. S. manufacturer and supplier of polyvinyl formal, no longer supplies Formvar for snowflake replication unless you can convince them you really need it and you will follow all the safety precautions the EPA requires industrial users of polyvinyl formal to follow.

Interpreting Cloud Conditions Based on Snowflake Observations

Type of Snow Crystal

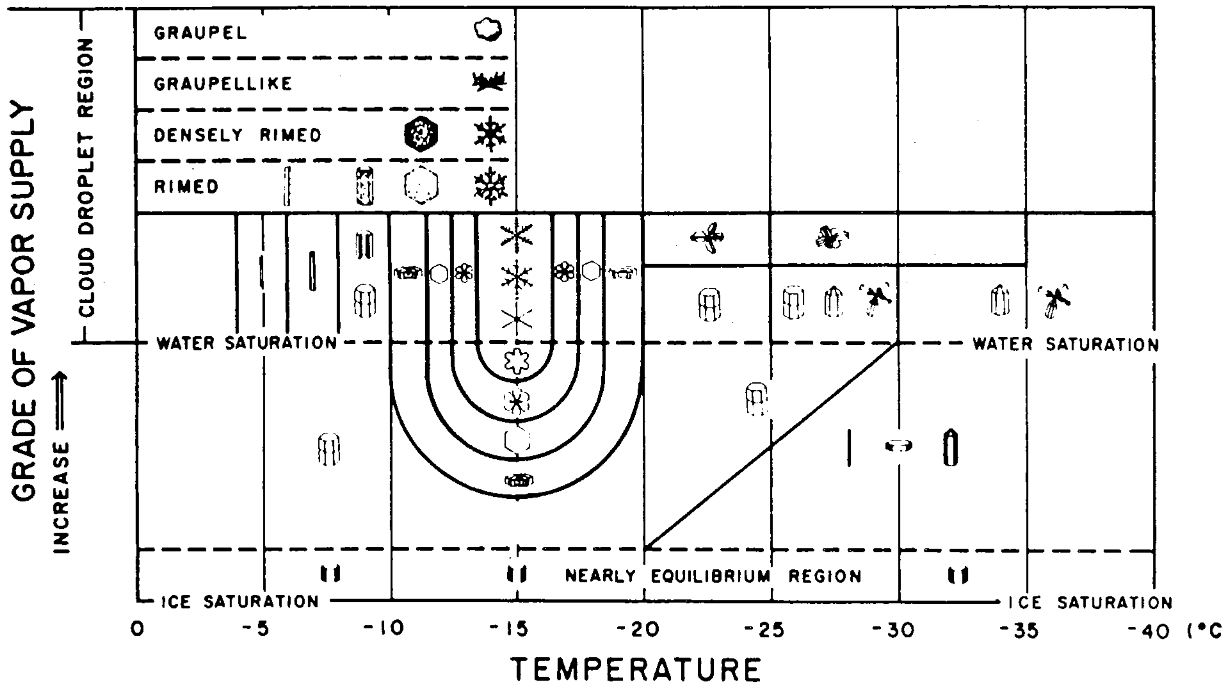


Fig. 15. Temperature and humidity conditions for the growth of natural snow crystals of various types. (Taken from Pruppacher and Klett, 1978 and Magono and Lee, 1966.)

Pristine snow crystals grow by nucleation and vapor deposition. This can occur anytime there are ice nuclei (or fragments of ice crystals which can serve as ice nuclei) present and the air has enough moisture to be supersaturated with respect to ice. As the bottom illustration shows, the air has very few particles that can serve as ice nuclei when the temperature is only a few degrees below the freezing point of water (though ice crystal fragments formed by the rime-splinter process or grown in a colder part of the cloud and falling down to the region that is only a few degrees below 0°C are not included in this chart). Even cloud droplets need ice nuclei in order to freeze at temperatures warmer than -36°C.

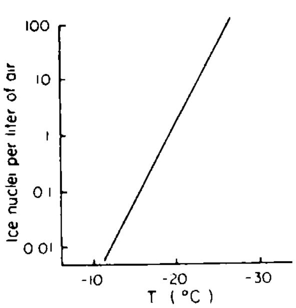


Fig. 16. Typical dependence of ice nucleus concentration on temperature. (Taken from Rogers, 1979.)

This is why liquid water droplets can exist in a cloud below 0°C. A supercooled liquid water cloud that is at equilibrium saturation with respect to water (i.e. the rate of cloud droplet growth through condensation equals the rate of cloud droplet decrease through evaporation) will be very supersaturated with respect to ice. At -10°C, the supersaturation with respect to ice is about 10%. At -20°C, the supersaturation with respect to ice is about 21%. These are very high considering that supersaturation with respect to water in cloudy air rarely exceeds 1%.

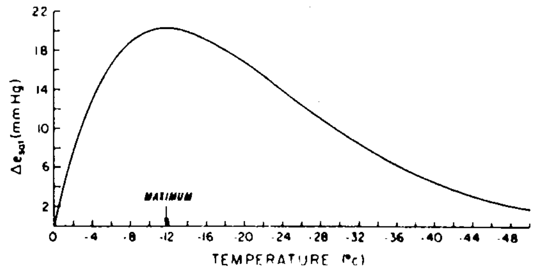


Fig. 17. Variation of Δe_{sat} = ($e_{sat,w}$ - $e_{sat,i}$) with temperature. (Taken from Pruppacher and Klett, 1978.)

As a consequence, once ice nucleation occurs, snow crystals can grow much more rapidly from vapor deposition than cloud droplets can. And indeed, snow crystals can grow at the expense of cloud droplets: cloud droplets will evaporate as they supply moisture for snow crystal growth.

All pristine snow crystals have one common basic shape, namely that of a hexagonal prism with two basal planes and 6 side planes. The different shapes snow crystals come in is due to the fact that the relative growth rate of different parts of this one basic shape varies with temperature and supersaturation.

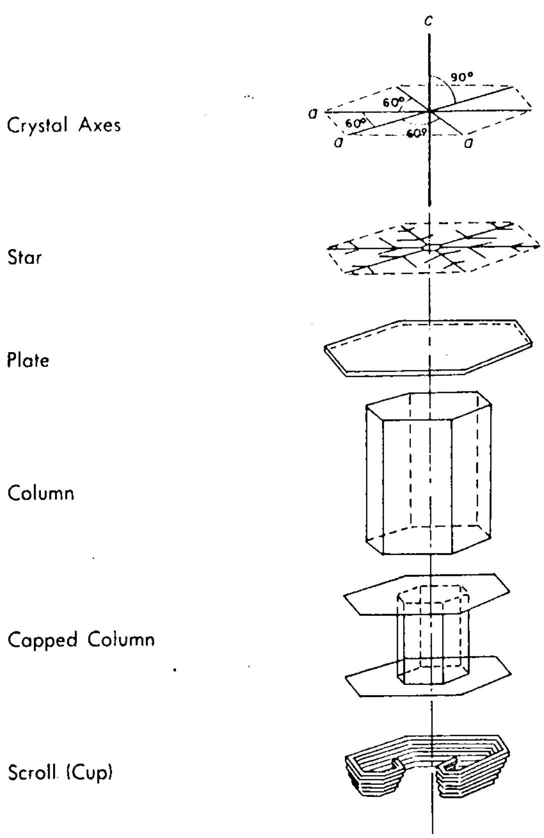


Fig. 18. Structural arrangement of the principal types of snow crystals in relation to the crystal axes of ice. (After an illustration by Swiss Federal Institute for Snow and Avalanche Research; From LaChapelle, 1969.)

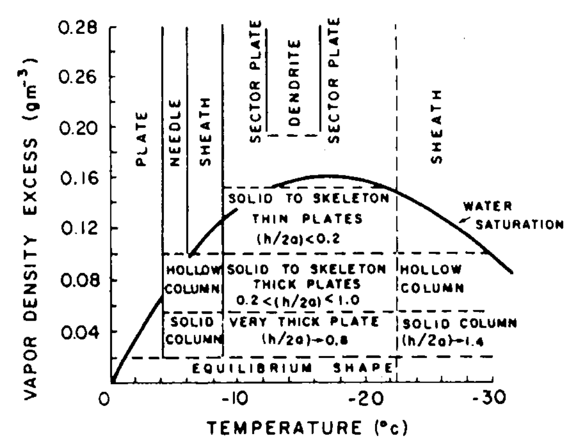


Fig. 19. Variation of ice crystal habit with temperature and vapor density excess. (Based on laboratory observation of Kabayashi, 1961; and Rottner and Vali, 1974; Taken from Pruppacher and Klett, 1978.)

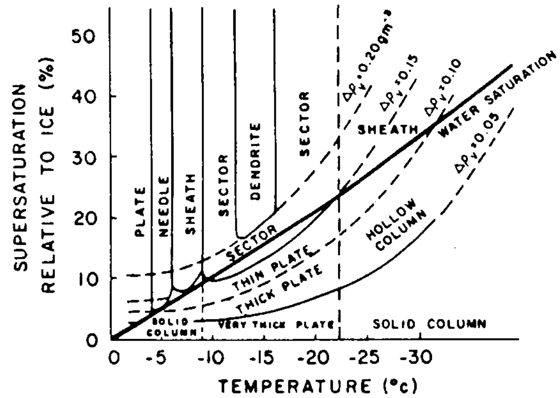


Fig. 20. Variation of ice crystal habit with temperature and supersaturation. (Based on laboratory observations of Mason, 1971; Hallett and Mason, 1958; Kobayashi, 1961; and Weissweiler, 1969. Taken from Pruppacher and Klett, 1978.)

Unfortunately, the preferential growth direction often undergoes cyclic change as temperature or humidity conditions vary. This means that, for example, at a fairly high amount of vapor supply present in a supercooled liquid water cloud, sector plates grow at two distinct temperatures. And just by seeing a sector plate, you won't be able to know which temperature region it grew in, but you can narrow down the cloud conditions.

However, not all snow crystals grow at two or more temperature and humidity conditions. When you refer to the large chart of temperature and humidity conditions of natural snow of various types by Magono and Lee at the top of this section to determine cloud conditions from the crystals you collected, you will find that some snow crystals grow only at specific temperature and humidity conditions such as dendrites which grow in the presence of water vapor in excess of water saturation from about -12°C to -17°C.

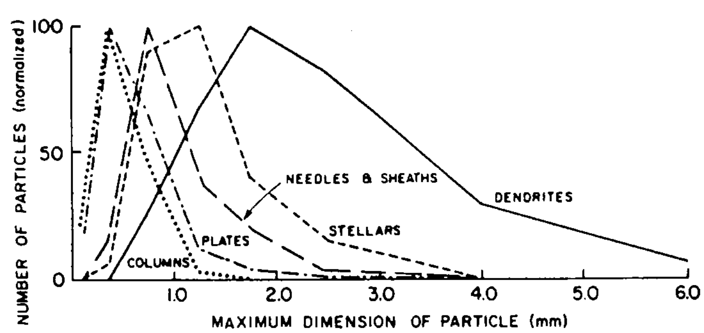


Fig. 21. Size distribution of snow crystals collected at Alpental Base, Hyak, and Keechelus Dam, State of Washington. (From Hobbs et al., 1972; Taken from Pruppacher and Klett, 1978.)

Amount of Riming

The growth rate due to riming is equal to the cloud liquid water content times the volume the falling ice particle sweeps out per unit time times the collection efficiency factor. The part that is relevant to interpreting cloud conditions is that the speed of riming is proportional to the cloud liquid water content. The higher the liquid water content, the faster riming occurs.

Referring again to the chart of temperature and humidity conditions for the growth of natural snow crystals, you'll notice it has a place for rimed, densely rimed, graupellike and graupel particles in a region of very high amounts of vapor supply corresponding to the region of high liquid water content.

A snow particle formed as a result of riming is called a rimed snow crystal during the initial stages of riming when the original snow crystal features are still well distinguishable. When the features of the primary snow particle are no longer visible, the particle is called a graupel, soft hail particle, or snow pellet. Graupel particles usually have maximum dimensions of less than 5 mm.

Graupel is opaque white due to the presence of a large number of air capillaries in the ice structure. It usually has a bulk density of less than 0.8 g cm^{-3}. Graupel may have a conical, rounded, or irregular shape. Graupel may also originate as a frozen drop and grow by riming to a roundish or irregular, semi-transparent particle of bulk density 0.8 to 0.99 g cm^{-3}, sometimes called small hail.

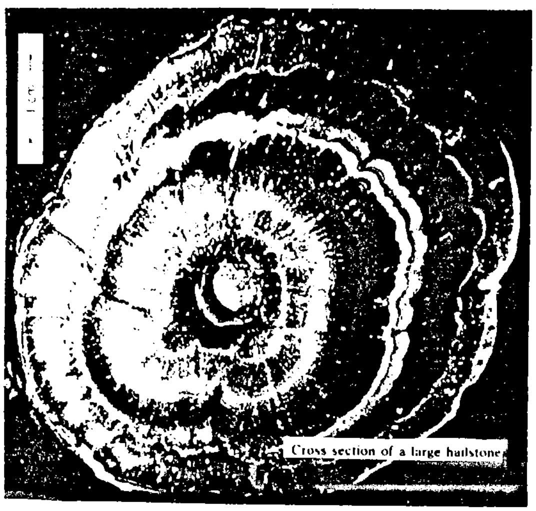


Fig. 22. Cross section of a large hailstone, showing the characteristic layered or onionskin structure. (Taken from Rogers, 1979.)

Graupel particles grown by riming are called hailstones if their maximum dimensions are typically larger than 5 mm. Hailstones have a roundish, ellipsoidal, or conical shape often with lobes, knobs, or other protuberances on the surface. Hailstones usually have diameters of a few centimeters, and large hailstones may have a major axis length as large as 6 to 8 cm. The cross section of a hailstone exhibits an onionlike layered structure with alternating opaque and clear layers caused by the presence of more or less numerous air bubbles.

Rimed ice crystals and graupel are formed in clouds which contain both ice crystals and supercooled droplets. Graupel is prevalent in the region of high liquid water content. A preference for graupel formation at moderate liquid water contents has also been noted at -10°C where more isometric crystal shapes prevail. In such clouds both snow crystals and frozen drops may serve as embryos for graupel formation. In clouds with sufficiently large updrafts, riming may continue until hailstones are produced.

Hailstones collected at the ground are usually hard ice particles, but in a few field studies, 'soft' spongy hailstones which consist of ice-water mixture have been found. Such ice-water mixtures are produced when the latent heat released during growth is not exchanged efficiently enough between the hailstone and its environment to allow all the water collected by the hailstone to freeze. That portion of the collected water which immediately freezes produces a skeletal framework or mesh of dendritic ice particle, in which the unfrozen portion of the collected water is retained like a sponge whose surface temperature is at 0°C. Several investigations found that water embedded in the ice structure of some hailstones comprised up to 16% of the total mass.

Amount of aggregation

Aggregates are formed when snow crystals collide and get stuck together. The three main factors influencing aggregation are snow crystal concentration, snow crystal shape, and environmental temperature.

Snow crystal concentration is important because snow crystals can't aggregate if they don't collide and the higher the concentration of snow crystals, the more likely collisions become. Roughly the rate of aggregation is proportional to the square of the ice crystal concentration.

Most aggregates are made up of plane or spacial dendrites because of their shape. Their intricate, fernlike arms will often get stuck together during a collision. Also, spacial dendrites settle through the air faster than plane dendrites; thus, a mixture of these two branched crystal forms favors the formation of aggregates.

Hobbs et al. (1974) and Rogers (1974) established that the probability of aggregation is highest near 0°C. This is because near 0°C, snow crystals have a waterlike film on them that freezes when the snow crystals touch and the film is no longer on the surface but rather in the middle of the two crystals. With decreasing temperature, the probability of aggregation decreases slightly except for a secondary maximum near -12 to -16°C where dendritic growth is dominant.

If the aggregates you have consist of dendrites, the amount of aggregation can't tell you much about the cloud conditions you don't already know. If, however, the aggregates are made up of other crystals, then you know they passed through air about -5°C or warmer. Aggregation can occur in the cloud and below the cloud any time before the crystal lands, so aggregation itself can't tell you exactly where this -5° to 0°C air is located.

Most aggregates have diameters between 2 and 5 mm, although maximum aggregate diameters may be as large as 15 mm. The maximum dimension of aggregates is largest near 0°C. Aggregates of columns and needles tend to stay small, while aggregates of dendrites tend to become large.

Rauber (1985) found, in winter storm systems over the mountains of Northwest Colorado, that the primary components of aggregates were planar dendritic crystals and radiating assemblages of dendrites. When dendrites were present in the precipitation, aggregation occurred independently of surface temperature and precipitation rate. Significant aggregation was not observed when dendritic crystals were not present. A warm surface temperature was not found to be an important condition for aggregate formation in these clouds.

Yeh et al. (1986) found, based on aircraft measurements in the stratiform region of mesoscale convective complexes, that aggregation starts in the upper, colder than -13°C layers, but that it becomes more efficient in the lower layers near the melting zone.

Favorable conditions for aggregation may also include a relative lack of graupel. The cause for this is assumed to be graupel's tendency, due to greater fall speed, to crash into aggregates and break them up. Another reason is that small amounts of supercooled cloud droplet water, which causes a little riming and may serve as an adhesive agent in the aggregation of snow particles, is not a condition that favors graupel formation. Whereas larger amounts of super-cooled liquid water may result in small aggregate clusters being readily converted to graupel particles.

In recent years, observational evidence suggested that aggregated snow particles comprise an important component of the total precipitation falling from a variety of cloud systems, including the stratiform regions of the winter monsoon cloud clusters (Houze and Churchill, 1984), the mesoscale rainband of extratropical cyclones (Matejka, Houze, and Hobbs, 1980), the winter stratiform clouds in California Valley (Stewart, Marwitze, Pace and Carbone, 1984), the hailstorms in Colorado (Heymsfield and Musil, 1982), the winter orographic cloud systems over the Northern Colorado River Basin (Bauber, 1985), the mature hurricanes (Jorgensen, 1984) and the stratiform region of midlatitude mesoscale convective systems (Yeh, Fortune and Cotton, 1986). The investigation of the shape, dimension, bulk density, number concentration, and compounds of aggregates is important for the study of cloud and precipitation systems.

Acknowledgements

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SNOWFLAKE OBSERVATION RECORDS

Date______________ Location______________________ Altitude___________ Observer_________________

Sampling time .... Winds	Exposure time .... Cloud base height	Air T°C ...... Cloud top height	Number	Average size	Mode size	Max size	Type of individual crystal or type (simple or mature) of aggregate, and amount of riming. Also, description of types of crystals in aggregates including estimate of the average number of each type of crystal.

SNOWFLAKE OBSERVATION RECORDS

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