Snow Particle Morphology in the Seasonal Snow Cover

Abstract

Snow precipitation degenerates rapidly once it reaches the ground. A wide variety of particle types develop in seasonal snow covers, thus leading to a wide range of snow properties. The most common varieties of particles are shown here. The physical processes responsible for the growth and development of these particles are described in general terms, although these processes are not understood as well as the processes of crystal growth in the atmosphere. The heat and mass flows associated with the development of these crystals in the snow cover are complicated because of snow's complex geometry.

1. Introduction

An introduction to the wide variety of ice particle morphologies in the seasonal snow cover is given here. Because a wide range of morphologies normally develops, the important material properties of the seasonal snow cover also are highly variable. That the seasonal snow undergoes very active and continuous changes should not be surprising; the snow is often at or close to its melting point, the particles are in intimate contact, the surface area per unit volume is very large, and the snow surface experiences constantly changing thermal conditions. This is a sure prescription for constant change or metamorphism. In fact, snow usually begins "destructive metamorphism" as soon as the precipitation reaches the ground. Figure 1 shows a broken snowflake in an early stage of the process in which it loses its sharp crystalline faces and develops well-rounded branches. Eventually this process leads to the well-rounded crystals shown in Fig. 2.

Perhaps the best known and most dramatic metamorphism is the recrystallization from well-rounded (Fig. 2) to highly faceted crystals (Fig. 3). These and other ice particle types are described later. First, a brief history of observations of the particles in the snow cover is given.

2. Snow cover observations

The relatively recent notice of the rich variety of particle types in the seasonal snow cover (e.g., Wolley, 1858) is in sharp contrast to over 400 years of observations of snow crystals grown in the atmosphere (see Frank, 1982). Not only have the observations lagged, but our understanding of the physical processes has lagged as well. For example, the well-known Nakaya (1954) diagram displays the different crystal forms of snow crystals as dictated by the temperature and supersaturation in the atmosphere, but reveals nothing about the growth of the highly rounded crystals shown in Fig. 2. Perhaps the striking hexagonal symmetry, the delicate frame, the high visibility of falling snow, and the multitude of photographs (e.g., Bentley and Humphreys, 1931) account for the general awareness of the morphology of snowflakes.

Systematic observations and explanations of seasonal snow morphology began in the Swiss Alps with the work of Seligman (1936) and Bader et al. (1939). Interest grew internationally (e.g., de Quervain, 1954; Yosida et al. 1955; Kuzmin, 1957; Giddings and LaChapelle, 1962) because of the awareness of the great variations in snow properties with changes in particle shape. Much of this earlier work was centered on the transition from the highly rounded to the highly faceted crystals shown in Figs. 2 and 3, respectively. Many other snow particle types are equally interesting (see Colbeck, 1982), although work on them has been even more recent. The most important forms are outlined in Table 1 and described later; some suggestions are given about their formation. While it is clear that interest in their growth is lagging interest in the growth of snowflakes and hailstones in the atmosphere, our understanding of the particle morphology of snow cover is making rapid advances through use of information generated by cloud physicists (e.g., Hobbs, 1974) and crystallographers.

The outline of seasonal snow morphology given in Table 1 is, like previous attempts to categorize snow, arbitrary and subject to revision as we increase our understanding of the processes and conditions. It begins logically with the source, but then divides snow on the ground arbitrarily into three categories—dry snow, wet snow, and a menagerie of mixed processes. Most snow particles can be classified adequately as IIa, IIb, IIIa, or IIIb, although the other groups can be quite important for particular purposes. The headings of the subsections of Sections 3, 4, and 5 correspond with the lettered forms listed under II, III, and IV, respectively, in Table 1.

3. Dry snow

a. Equilibrium form

At slow growth rates, crystal forms develop that minimize the total surface free energy of an entire crystal (see the Appendix—Glossary of terms). At these slow rates, crystals grow by vapor condensation on the surface followed by the incorporation of molecules into vacant sites on the surface, a process similar to the growth of liquid droplets. As we might expect, the shape of a crystal formed at very slow growth rates can be described approximately by equilibrium thermodynamics, and the shape of such a crystal can be determined through the construction of a Wulff plot (see Appendix). The equilibrium shape of an ice crystal in air generally is
FIG. 1. A broken snowflake in an early stage of "destructive metamorphism." The sharp crystalline faces are disappearing as the surfaces become rounded.

FIG. 2. Highly rounded, equilibrium form of snow crystals. This form dominates in seasonal snow at high temperatures and low temperature gradients. These grains are bonded together by sintering.

FIG. 3. Highly faceted, kinetic growth form of snow crystals. This form dominates at high temperature gradients. These depth hoar crystals are cohesionless because of the lack of sintering during rapid growth.

thought to be a thick hexagonal plate, but, at higher temperatures, the equilibrium form is well rounded. Apparently, the surface transition layer, or Faraday's "liquid-like layer," reduces the surface energy differences among the crystallographic faces. The exact shape of the equilibrium form is not well established, although the slowly growing crystal in Fig. 2 suggests a prolate spheroid. This elongated shape commonly is observed in snow and may be the true equilibrium shape at temperatures just below the melting point. Sintering, or the movement of molecules to the interparticle contacts, occurs readily during the growth of the well-rounded form and gives snow its strength. As described next, sintering is reduced noticeably at large growth rates, thus leading to the cohesionless depth hoar crystals shown in Fig. 3.

b. Kinetic growth form

The growth rate of ice crystals in a dry snow cover decreases with increasing snow density, but increases with the temperature gradient through the snow cover. Apparently the supersaturation over the bottom side of an ice crystal is determined largely by the temperature difference between it and the crystals just below it. Thus, the vapor pressure or supersaturation increases with the temperature difference between individual crystals, which, in turn, increases with crystal spacing and temperature gradient. The crystal spacing is greater for less dense snows and the temperature gradient is greater for shallow snow covers during periods of cold weather (the ground surface normally is warmer than the snow surface during winter).

If the supersaturation over the growing crystal exceeds a critical value, the growth proceeds rapidly by the propagation of distinct layers across the crystalline faces. The rate of movement of these layers varies with orientation in the crystal, so that some faces tend to grow out more quickly than others. This gives rise to the highly faceted crystals shown in Fig. 3, a clear departure from the well-rounded form shown in Fig. 2. These rapidly growing crystals are called the kinetic growth form because the surface kinetics determines their shape. Since equilibrium thermodynamics has little to do with their growth, they do not readily develop interparticle strength by sintering. Accordingly, a layer of these highly faceted crystals (usually called depth hoar) can destabilize a snow cover and lead to avalanches. These faceted crystals grow most rapidly

TABLE 1. Outline of processes and conditions determining seasonal snow morphology.

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FIG. 5. Surface hoar crystals. These grow on cold, clear nights by vapor flow downward to the snow surface.

in the lower layers because both the diffusion of water vapor in air and the vapor pressure difference between sources and sinks increase with mean temperature. During the most active growth, the highly faceted crystals are as cohesionless as oven-dried sand, while at intermediate growth rates they can retain some strength.

The actual mechanism for crystal growth is vapor transfer among neighboring ice grains due to temperature differences, or Yosida et al.'s (1955) "hand-to-hand delivery of water vapor" upward through the snow. At lower temperature gradients the vapor transfer is slower, so that the growth rate is slower and the well-rounded equilibrium form dominates. When the temperature gradient exceeds 10–20°C/m (depending on snow conditions), the rounded grains disappear and are replaced by faceted grains without a noticeable increase in snow density. This process begins with the growth of faceted crystals on the lowermost, coldest portions of chains of crystals, as indicated by arrows.

Another type of highly faceted crystal (Fig. 5) grows on the snow surface and is called "surface hoar." These crystals form on cold, clear nights when the snow surface is cooled by radiating into space. Vapor moves downward to the cold surface from the warmer air and rapid crystal growth occurs. These crystals also are poorly bonded and, once buried by subsequent snowfalls, can become surfaces for future avalanche release.

c. Transitional form

Things seldom fall neatly into two classes in nature, and it is not surprising that crystals with mixed facets and rounded portions can be observed. Apparently some crystallographic faces develop facets more readily than others and produce mixed crystals at intermediate growth rates (see Fig. 6). These intermediate growth rates probably correspond to temperature gradients that are close to the critical value mentioned previously.

Another version of the mixed crystal (Fig. 7) appears when rapid growth ceases. After developing as a fully faceted crystal at a high growth rate, a depth hoar crystal can lose its sharp corners and edges to rounding, much as the snowflake shown in Fig. 1. The onset of warmer weather reduces the tempera-

FIG. 6. Crystals with mixed faceted and rounded portions at an intermediate growth rate.
4. Wet snow

Although most seasonal snow falls at a subfreezing temperature, it is eventually wetted by rain and/or melt. Upon the introduction of the water, snow undergoes major changes in its grain morphology and in all of its important properties. Like dry snow, wet snow can be described by two classes: well-bonded and cohesionless. While dry snow undergoes a sharp transition at a critical growth rate (perceived as a critical temperature gradient), wet snow undergoes a sharp transition at a critical liquid water content (Figs. 8 and 9).

a. Low liquid content

Grain clusters form in wet snow with a low liquid content because tightly bonded clusters minimize the total surface energy in a material with all three types of interfaces: liquid-to-solid, vapor-to-solid, and liquid-to-vapor. Strong bonding prevails within a cluster, although the clusters are not bonded as strongly to their neighbors. This allows wet snow to retain a low density en masse, although the density of each individual cluster may be close to that of solid ice.

The formation of these clusters and the growth of grains in wet snow have long been attributed to melt-freeze cycles (Sellman, 1936). This is unfortunate, since the clusters form and the grains grow faster in the absence of temperature cycles. Clusters form and grains grow in order to minimize surface free energy; they do so most quickly in the presence of liquid water and any amount of time spent below the melting temperature can only slow matters down. As discussed in the next section, melt-freeze cycles are important, but clusters form and grains grow without these cycles (see Fig. 8).

Grain growth by cannibalism, the consumption of smaller grains by larger grains, occurs in both wet and dry snows, but for very different reasons. In wet snow, the snow mass is macroscopically isothermal and the temperature variations occur only locally among the grains, with smaller particles being at a lower temperature. The local temperature differences may be small, but the path length for heat flow among neighboring grains is also small, so the heat flow can be large. Thus, the small grains melt rapidly as the large grains grow, and, as the smaller sources disappear, grain growth quickly slows. This typically happens at a grain size of 0.5–1 mm.

In dry snow, the vapor pressure at thermodynamic equilibrium over the ice crystals decreases with increasing size, whereas in wet snow, the melting temperature is lower for smaller particles. Since dry snow is always subjected to changing surface conditions and therefore to an ever-changing temperature profile, the small temperature differences that could arise among particles of various sizes are overwhelmed by the overall gradient. Accordingly, the heat and vapor flows are predominantly upward in dry snow. These upward heat and vapor flows lead to the rapid disappearance of the small particles in dry snow, whereas in wet snow, the small particles disappear because of heat flows among neighboring grains of different temperatures.

b. High liquid content

Grain growth in wet snow above a critical liquid content (only about 7% by volume) occurs more quickly than at lower liquid contents. The melting temperature-particle size dependence is stronger in the higher range of liquid contents and the liquid area available for heat flow is greater. The transition between these two liquid content categories, usually termed the pendular (low) and funicular (high) regimes, occurs suddenly in any given pore. This sudden change in regimes is very important in wet snow because it leads to equally sudden changes in many important properties. The material strength is particularly important; it is reduced drastically at higher liquid contents. Grain clusters and their large grain boundaries are unstable at high liquid contents; the clusters shown in Fig. 8 would break down into the cohesionless particles shown in Fig. 9. Perhaps the most visible example of wet snow's lack of strength at large liquid contents is seen on highways. Vehicle traffic over wet snow on road surfaces causes either rapid compression of the snow into ice or splashing. At low liquid contents where wet snow develops considerable bond strengths, compaction into ice is likely. However, at high liquid contents where the snow is cohesionless, the slushy snow can be splashed aside easily.

The transition to high liquid contents also is thought to be responsible for releasing wet snow avalanches. This probably occurs by water retention at a buried crust, followed by loss of strength along that buried layer.

The reason for the lack of grain boundaries at high liquid contents apparently can be explained by the temperature depression caused by stress at the grain contacts. The contacts act as stress risers, and crystalline boundaries are naturally
FIG. 8. Metamorphic sequence starting with a wet snowflake. At a low liquid content, grain clusters develop rapidly in freely draining wet snow. The liquid is held along the grain boundaries and at liquid-filled veins at triple-grain junctions. The air temperature was above freezing throughout this period. a) Fresh snowflake ($T \approx +2^\circ C$); b) 5 h old; c) 10 h old; d) 28 h old; e) 53 h old.

weak anyway. The disintegration, or “candling,” of lake ice along crystalline boundaries during the spring thaw and the cohesionless nature of ice particles in laboratory ice-water baths attest to this weakness. (If you are not familiar with these examples of cohesionless ice particles, examine the ice cubes in your next cocktail.) These observations, however, are different from Faraday’s (1860) classic experimental observation of suspended ice spheres. Faraday found that suspended spheres stick together even when placed in water. I once tried to explain this contradictory evidence on the basis of either impurities or electrical charges, but found that Faraday’s conclusion was correct for all of the parameters I could control. Examine ice cubes submersed in water and try to reconcile your observation with Faraday’s.
FIG. 9. Cohesionless and well-rounded grains in wet snow at a high liquid content. Photographed through crossed polarized filters.

5. Mixed processes

a. Melt-freeze grains

Although melt-freeze cycles are not responsible for grain growth or grain clusters in wet snow, these cycles do produce a distinctive type of grain in both seasonal and glacial snow covers. The individual particles in grain clusters like the ones shown in Figs. 8e and 10a are clearly distinguishable single crystals of ice. With repeated melt-freeze cycles, these crystals lose their individual character and visually become an amorphous version of the grain cluster (Fig. 10b). If subjected to strong solar radiation, these amorphous clusters can break down along their crystal boundaries and the individual crystals can reappear.

b. Surface melt crystals

Multicrystalline grains tend to break down into single crystals when subjected to solar radiation at the surface of a snow cover, which is why melting snow surfaces often consist of cohesionless single crystals and tend to be weak and slushy. In a strong solar radiation field, the surface layer of 1–2 cm can be scraped away easily, while the underlying layer, which consists of well-bonded grain clusters as shown in Figs. 8e and 10a, is much stronger. This strong spatial gradient in snow particle morphology and snow strength quickly disappears along with the sun, a fact long used by skiers who recognize the different snow surface conditions in the shadows of trees. This surface disaggregation probably affects the albedo of the snow cover, since albedo generally is a strong function of grain size, which varies greatly between slushy and well-bonded snows.

c. Wind and sun crusts

Wind-blown particles on the surface often form fine-grained crusts that subsequently are buried and give rise to the ice layers described later. The wind action breaks the particles into smaller pieces and rapidly promotes rounding, much as wave action does to beach sand. Unlike beach sand, however, wind crusts on snow are strengthened greatly by rapid sintering—the deposition of vapor at the particle contacts, as shown in Fig. 11. These strong crusts are well known to skiers who venture off the machine-packed trails. Of course, diurnal cycles of solar radiation can produce the same result, but by a very different mechanism. The production of very small amounts of meltwater by solar radiation absorption in the top few centimeters of the snow cover can cement the grains together quickly because all of the meltwater must flow to the bonds before refreezing.

d. Melt-freeze layers

When surfaces are buried by subsequent snowfalls, they become potential sites for meltwater retention and refreezing. This happens most readily in shallow snow covers in temperate climates, where the snow cover consists of many small
layers and melt periods typically are mixed with the refreezing of the entire snow deposit. There are several reasons for the preferential retention of downward percolating water at these buried horizons. As explained previously, these horizons are often wind crusts consisting of fine grains that hold more capillary water in their small pores. Also, any difference in pore size between layers can cause some liquid retention at the base of the fine-textured layer. When subjected to refreezing, this retained water further decreases the size of the pores so that a positive feedback arises. The resulting "ice layers" are rarely impermeable, but do restrict the downward flow of water, at least during the onset of heavy melt in the spring. Like the melt-freeze grain cluster shown in Fig. 10b, ice layers break down under the influence of solar radiation. They also break down when the infiltrating meltwater is retained on their upper surfaces, mostly by enlargement of the triangular veins at triple-grain junctions, as shown in Fig. 12.

6. Summary

The snow falling from the atmosphere undergoes rapid changes as soon as it reaches the ground (Fig. 1). Snow particles on the ground are as variable as, but very different from, snow crystals in the atmosphere. A wide variety of ice particles from seasonal snow covers were shown here. These ice particles can be classified either according to shape or by the metamorphic processes that produce them. In Table 1 they have been classified according to the dominant process of formation or condition.

Snow that has never been wetted takes on a well-rounded, equilibrium form at low growth rates and high temperatures (Fig. 2), and is well bonded by sintering. At large growth rates (characterized by a large temperature gradient), snow recrystallizes, with highly faceted crystals (Fig. 3) replacing the highly rounded ones. These highly faceted crystals are a kinetic growth form of the ice crystal and lack interparticle strength because of reduced sintering.

Once wetted, snow takes on very different morphologies and properties. This difference is most readily apparent in the high-frequency dielectric behavior because of the large dielectric constant of water as compared to that of ice or air. There also are major differences within the category of wet snow, depending on the water content. At low water contents...
(<7% by volume), wet snow is well bonded because the ice particles form into strongly bonded grain clusters (Figs. 8 and 10a). At high liquid contents, the snow tends to be cohesionless due to the weakening of the crystalline boundaries (Fig. 9).

Besides simply wet or dry snow, there are many processes that affect the morphology of the ice particles and the resulting properties of the snow. Snow particles often are subjected to a mixture of processes, which leads to a complicated grain structure. Wind action, sunshine, melting, and freezing are the most important of these processes. For example, once grain clusters form in order to reduce surface free energy at low liquid contents, melt-freeze cycles can reduce these grain clusters to amorphous forms in which the original ice crystals are no longer readily visible (Fig. 10b). Wind can break the particles and promote rapid sintering, leading to strong crusts (Fig. 11). Melting and subsequent refreezing of buried crusts leads to semipermeable ice layers of increased density and strength (Fig. 12).

A wide range of processes and conditions that lead to a wide variety of ice particle morphologies and properties in seasonal snow covers have been shown. The emphasis here has been on morphology, but much more information about the properties is available (see the series of reviews published with Colbeck, 1982). The processes that lead to these morphologies and properties are being investigated and a deeper understanding is emerging. The different types of ice particles in snow were observed and classified on the basis of morphology some time ago. With increased knowledge of the underlying processes, it seems reasonable to classify them on the basis of causes rather than effects. No doubt this classification will continue to evolve with our understanding of ice particle morphology in the seasonal snow cover.

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Appendix—Glossary of terms

Depth hoar—a highly faceted crystal that grows during periods of high temperature gradients. These crystals develop most rapidly in the lower, warmer layers.

Equilibrium form—the shape that develops at equilibrium when no crystal growth or shrinkage is occurring. This term is used loosely here to describe crystals that grow slowly.

Equilibrium thermodynamics—the basic assumption is that the water, water vapor, and/or ice are in thermodynamic equilibrium. This assumption is always approximate, since ice crystals in snow never stop growing or shrinking.

Grain clusters—a tightly bonded group of snow grains and/or crystals.

Kinetic growth form—the shape that develops at high growth rates when surface kinetics rather than thermodynamic equilibrium controls shape. Once the rapid growth ceases this shape is unstable.

Sintering—the movement of molecules to the interparticle contacts, which develop strength as they accumulate mass. Most of the mass transfer is by vapor movement through the air. The higher vapor pressure over the rounded particles is the driving force.

Snow crystal—an ice particle consisting of a single crystal of ice.

Snow grain—an ice particle consisting of one or more crystals of ice.

Surface free energy—in the simplest sense, this is the energy required to create a unit area of additional surface area. This usually varies with direction in a crystal.

Surface hoar—a highly faceted crystal that grows very rapidly on the surface during clear, cold nights.

Surface transition layer—a disordered surface or “liquid-like” layer that covers the crystalline surface in order to achieve a stable transition between the ice and water vapor. The thickness of this layer increases greatly as the melting temperature is approached.

Wet snow—snow at the melting temperature and containing liquid water. The liquid water content is highly variable in wet snow.

Wolff plot—given the surface free energy of every crystallographic face, the shape of the crystal at equilibrium can be constructed using this simple technique. For an example, see Herring (1953).

References


