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Formation of Snow Crystals

SNOW, ICE AND PERMAFROST
RESEARCH ESTABLISHMENT
Corps of Engineers, U. S. Army

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FORMATION OF SNOW CRYSTALS

by Ukichiro Nakaya

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ABSTRACT

It is proposed that crystals of ice formed in the air be classified into snow crystals proper and ice crystals. The germs of snow crystals formed at high altitude and ice particles obtained by seeding are grouped as ice crystals. The relationship between meteorological conditions and crystal formation should be investigated separately for these two types. This classification will serve to eliminate possible confusion of the two types of crystals.

Experiments conducted by making various types of snow crystal proper artificially have shown that needles, irregular needles, and cup crystals are formed in the region of supersaturation above water saturation, while columns and spatial assemblies of plates are produced in the region between water and ice saturations. Dendritic crystals and the two kinds of plates appear both in conditions of supersaturation with respect to water and supersaturation with respect to ice.

In the snow-making apparatus, numerous minute droplets appear in the range of supersaturation with respect to water. They are about 1 micron in diameter and behave like water vapor in condensing on ice surfaces. The number of these minute droplets agrees well with the total concentration of nuclei in air as measured by previous investigators.

Study of the variety in shape of ice crystals obtained by seeding, examined in the light of our knowledge of artificial snow production, and electron-microscope study of the snow crystal nucleus give rise to a new theory of snow crystal formation. First the ice crystal is formed by spontaneous transformation of a supercooled droplet at cirrus temperature; or by natural or artificial seeding at higher temperatures; or by direct condensation of water vapor on a solid nucleus. Then snow crystals proper grow from these ice crystals, which act as germs. Most snow crystals proper are made not only by sublimation of water vapor, but also by condensation of minute droplets on these ice crystals. Most commonly, the minute water droplets are formed on the condensation nuclei during supersaturation with respect to water.

The peculiar action of the minute water droplet in condensing, like water vapor, on the ice crystal surface may be due to the surface diffusion of H_2O molecules. The metamorphism

of snow particles on the ground is assumed by many workers to be chiefly due to surface diffusion of H_2O molecules. It is suggested that similar surface phenomena take place in the formation of snow crystals in the air.

INTRODUCTION

Twenty years of investigation of natural and artificial snow crystals, carried out by Nakaya *et al.* (1933-38) and Hanajima (1942-45) in the laboratory at Hokkaido University, Sapporo, Japan, leads us to conclude that snow crystals may be classified into two categories: snow crystals proper and ice crystals. The snow crystal proper is the one observed on the earth's surface, and popularly called snow crystal. Subsequently, this is simply called "snow crystal." This crystal must have been born at a high altitude and grown into the ordinary form observed on the earth's surface while falling through various strata of the atmosphere. Its initial stage, seen in the cirrus cloud or ice fog, is the crystal of ice formed in the air by condensation of water vapor by sublimation[1] and is not different in nature from the snow crystal proper. However, as the dimension is quite different, it is convenient to differentiate this germ of snow from snow crystal proper. Let us call it "ice crystal."

Figure 1 contrasts a snow crystal and ice crystal. The small hexagonal plate (Fig. 1b) is an example of the germ of snow crystal, observed on the earth's surface at Mt. Tokachi, Hokkaido, at 1030 meters above sea level. A very similar hexagonal plate is seen at the center of the snow crystal of fern-like type (Fig. 1a). The dendritic nature of the snow crystal (Fig. 1a) is significant, especially when considering the relationship of crystal form to meteorological conditions.

Crystals transformed from supercooled water droplets by seeding are also called ice crystals. We cannot draw a definite line between snow and ice crystals, but it is convenient to group them as shown in Table I.

In the formation of a snow crystal in nature, the ice crystal is formed first. The ice crystal may be produced by the spontaneous transformation of a supercooled water droplet at cirrus temperature, or by natural or artificial seeding at higher temperatures, or by direct condensation of water vapor on a solid nucleus. Minute ice crystals are the most efficient seeding materials. All these processes cause small ice crystals, or germs of snow crystals, to appear in the atmosphere. The form and structure of the snow crystal which grows from this germ is determined by the meteorological conditions met *after* a germ is made. Ice crystal form may be controlled by different conditions than snow crystal form, especially when the seeding process is employed. This is one of the problems to be solved by future investigations. Classification of crystals of ice formed in the air into snow and ice crystals will be useful in eliminating possible confusion between the two.

TABLE I. DIMENSIONS OF SNOW AND ICE CRYSTALS AND CONNECTED PARTICLES

	Classification	Average size mm	micron
Snow crystal	fern-like crystal	4.0	4000
	ordinary dendrite	2.5	2500
	plate with extensions	1.5	1500
	simple plate	0.8	800
	Column	0.5	500
Ice crystal (observable in nature)	Ice fog or cirrus particle, larger	0.3	300
	ice fog or cirrus particle, smaller (initial stage of snow crystal)	0.1	100
Ice crystal (obtained by seeding)	ice crystal transformed from water droplet by seeding, larger	0.05	50
	the same, smaller	0.01	10
Cloud particle	fog particle	0.03	30
	ordinary cloud particle	0.01	10
	minute droplet	0.001	1
Nucleus	center nucleus found in snow crystal	0.001	1
	condensation nucleus or aerosol	0.0001	0.1
	AgI particle used for seeding	0.0001	0.1

RELATION BETWEEN SNOW-CRYSTAL FORM AND EXTERNAL CONDITIONS

The elements which control snow-crystal form were studied by means of an artificial snow-making apparatus. The method of making snow crystals (proper) is described in detail by Nakaya, Toda, and Maruyama (1938), and a sketch of the apparatus is reproduced in *Compendium of Meteorology* (Nakaya, 1951). Two concentric glass cylinders are held vertically, and a water reservoir is placed beneath the inner cylinder. The entire apparatus is put in a thermostat which is set in the cold chamber at about –30°C. The temperature in the thermostat is varied between –1°C and–25°C. The water in the reservoir is heated electrically and kept at various temperatures above 0°C. The warm water vapor is thus driven

[1] Detailed explanation of the term "condensation of water vapor by sublimation" is given under the heading "Mechanism of snow-crystal formation."

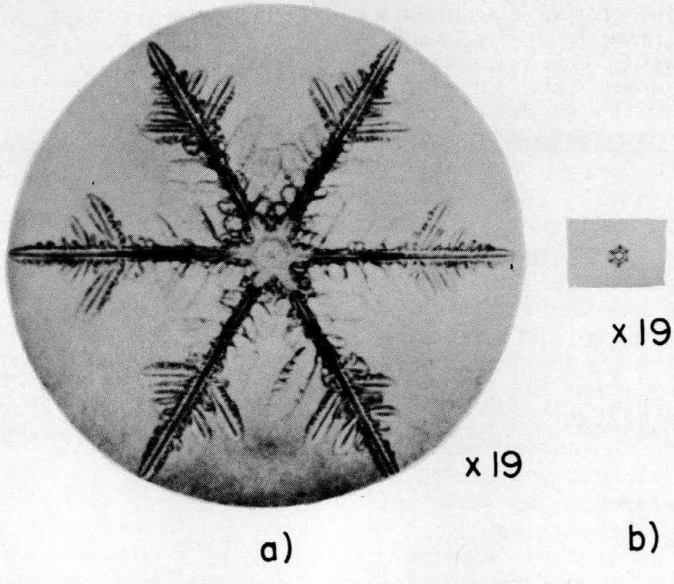


Figure 1. Comparison of Snow Crystal and Ice Crystal
(a) Snow crystal of fern-like type diameter = 3.7 mm.
(b) Ice crystal of plate type, diameter = 0.14 mm.

upward inside the inner tube, while the cooled air comes down through the space between the two cylinders, giving a nearly steady convection of water vapor. The snow crystal is formed on a thin filament at the upper portion of the apparatus, where the temperature is low.

In this apparatus, various forms of snow crystals observable in nature were produced artificially by changing the temperature of air, T_a, where the crystal is made, and the temperature of water in the reservoir, T_w. The latter is a measure of supersaturation. Thus it is concluded that at least the chief elements which control the form of a snow crystal are temperature T_a and the degree of supersaturation s. It has been generally believed that crystal form is determined by degree of supersaturation, but not by temperature. The well known theory of Volmer and Schultz (1931) considers only the supersaturation and not the temperature. According to aufm Kampe, Weickmann, and Kelly (1951), however, temperature may be substituted for supersaturation as the factor controlling ice crystal form, since the crystallization is considered to take place at water saturation, a function of temperature. This idea, that crystallization of ice in the air is controlled by the vapor density difference of water and ice saturation, which is a function of temperature, was used by Houghton (1950) in his theory of the rate of growth of ice crystals, with some successful results.

In our experiments, supersaturation does not necessarily mean excess of water vapor in the air. The upward current of air in the apparatus was found to contain a large number of minute droplets of about 1 micron or less in diameter. A known volume of this air was taken from the neighborhood of the spot of crystal formation, and the total water content was measured by a gravimetric method using P_2O_5; s is taken as

$$s = \frac{w + \rho'}{\rho_0} \qquad (1)$$

where w = liquid water content per unit volume, ρ = vapor density at saturation over supercooled water, and ρ_0 = vapor density over ice. The relation between T_w and s was determined experimentally, and a T_a-s diagram constructed (Fig. 2), which shows that each of the various types of snow crystals occupies a certain range. This experiment was carried out by Hanajima (1942-45) for 700 snow crystals of various types.

In Figure 2, the crystals are classified into eight types. Curve W shows the vapor pressure at water saturation. Note that needles, irregular needles, and cup crystals are formed above water saturation, while the columns and spatial assemblage of plates are produced in the saturation range between water and ice. Dendritic crystals and two kinds of plates appear both above and below water saturation; the former occur frequently above water saturation, the latter below.

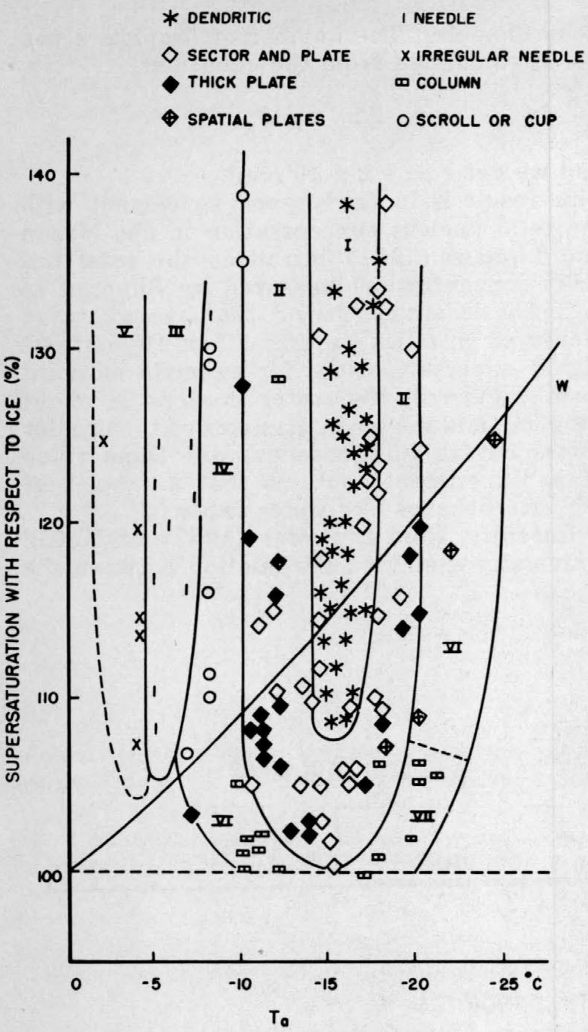


FIGURE 2. T_a-s DIAGRAM SHOWING CONDITION OF FORMATION OF VARIOUS TYPES OF SNOW CRYSTALS
From Hanajima (1942-1945)

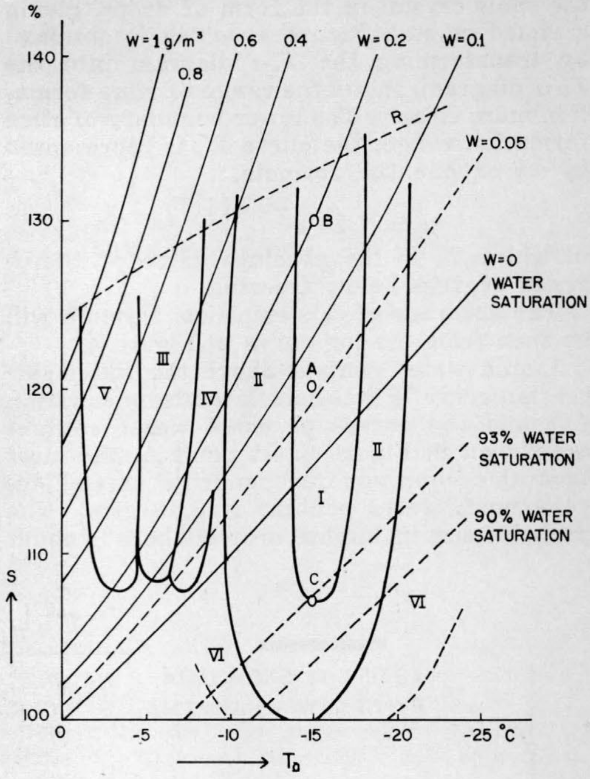


FIGURE 3. CURVES OF EQUAL WATER CONTENT IN THE REGION ABOVE SUPERSATURATION WITH RESPECT TO WATER

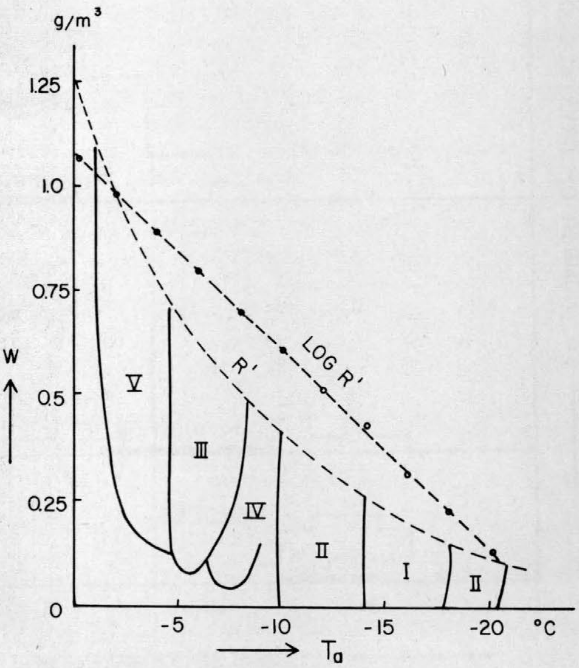


FIGURE 4. T_a-w DIAGRAM SHOWING RANGE OF RIME FORMATION
Rimed crystals form above curve R' (from curve R, Fig. 3).

The region above the water saturation curve *W* represents cloud-formation conditions. The numerous minute droplets of about 1μ in diameter which are observed in the upward convection current in our snow-making apparatus are produced in this region. This minute droplet shows a peculiar behavior; it does not freeze to the surface of snow crystal in droplet form but spreads over the ice surface, thus behaving like a vapor molecule in the process of condensation.

Rimed crystals, which are snow crystals with numerous fog particles attached, are frequently observed in nature. The fog particles are larger than the minute droplets discussed above. These larger droplets, say 20 or 30μ in diameter, appear in our artificial snow-making apparatus also, at higher supersaturation (above curve R, Fig. 3) and freeze to the snow crystal in the form of drops, giving a rimed crystal. Figure 4, which is obtained by transforming the T_a-s diagram into the T_a-w diagram, shows the range of rime formation more clearly. The lower boundary of rime formation range, the curve R′, is represented by an exponential formula,

$$w = 1.29\, e^{-0.111\, T_a}$$

in which T_a is the absolute value of Centigrade degrees below freezing.

The accuracy of this empirical formula will be seen from the log curve in Figure 4.

Liquid water content above the water saturation curve W was calculated from equation (1) and the curves of equal water content are shown in Figure 3. At point A, the most favorable condition for dendritic crystal development, water content is 0.06 g/m³. The probable size of minute droplets here is about 1μ in diameter. The number of droplets n per cm³ is calculated from the equation

$$w = \frac{4\pi}{3}\; n\, \rho\, r^3,$$

and we get $n = 1.2 \times 10^5/\text{cm}^3$.

This result is in fairly good agreement with the total nucleus concentration in air. Mason and Ludlam (1951) introduce the total nucleus concentration measured by Simpson in different localities, giving the average value measured in cities by $n = 1.5 \times 10^5/\text{cm}^3$. At higher supersaturation, for example at point B in Figure 3, the water content is about 0.2 g/m³, and the mean diameter of the droplet comes out as 1.5μ, assuming the same value of n. Experiment confirms that a droplet of this size behaves like water vapor.

Recently, Gold & Power (1952) of McGill University examined the relation between the

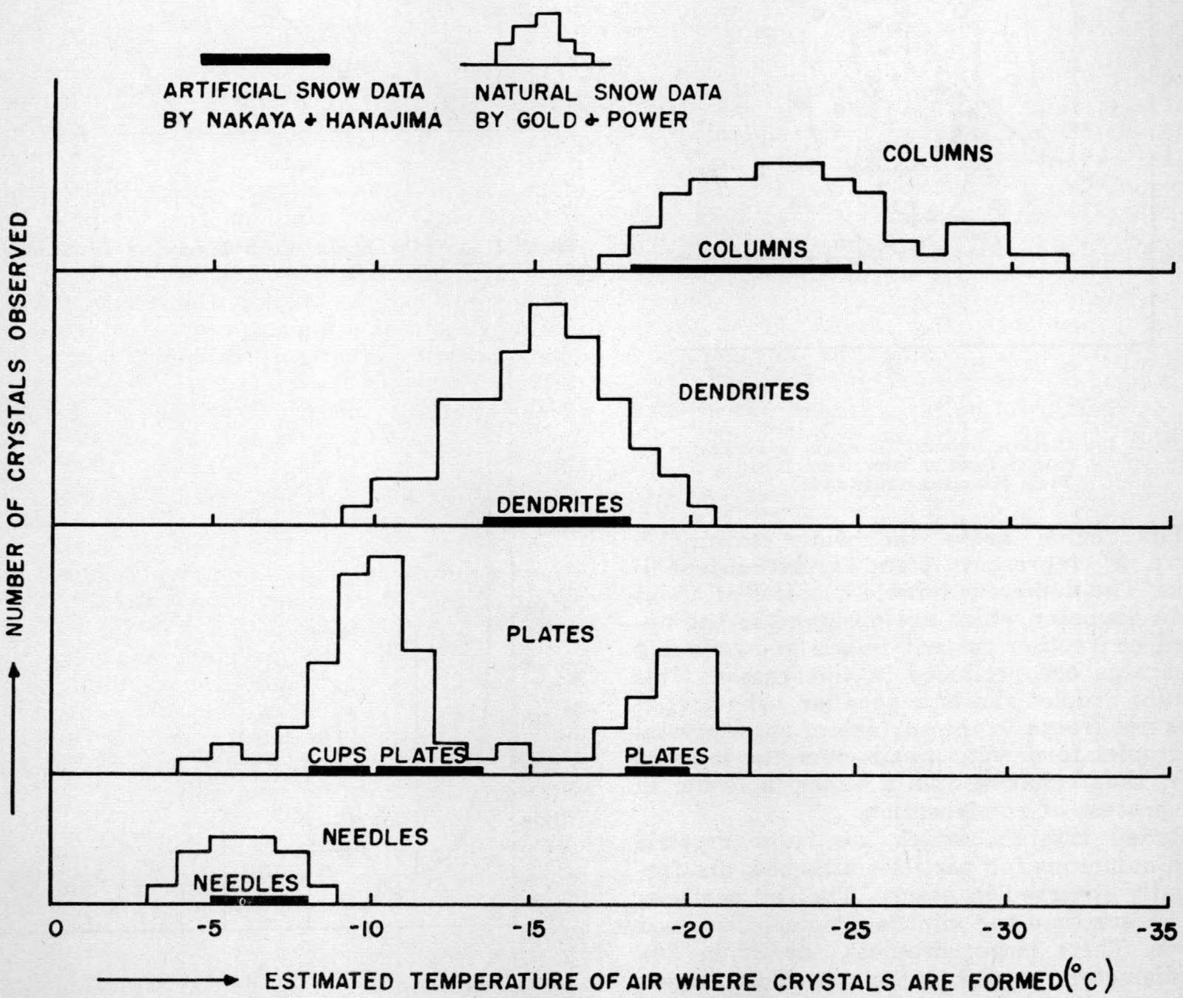


FIGURE 5. CONDITIONS OF FORMATION OF NATURAL AND ARTIFICIAL SNOW CRYSTALS

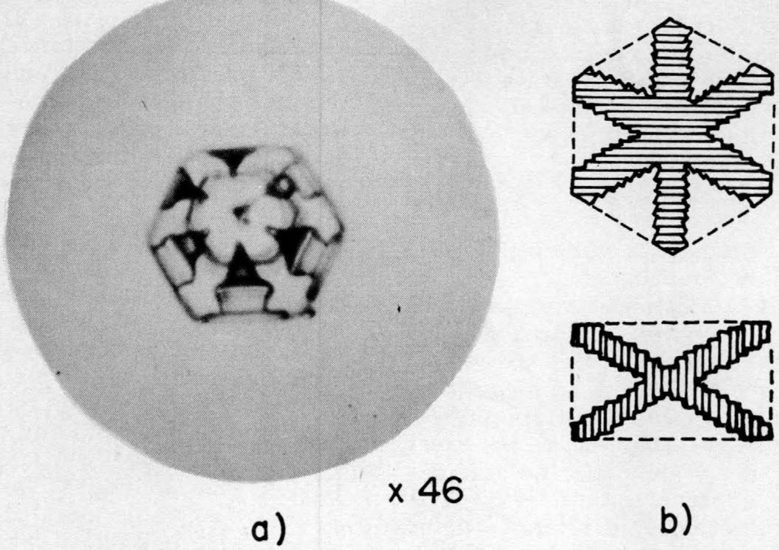


FIGURE 6. A HEXAGONAL PRISM OF SKELETON STRUCTURE
(a) Artificially made. (b) Elevation and plan. Shaded part shows ice material. Clear parts are the stepped hollows as seen in a crystal of NaCl.

shape of snow crystals (proper) observed on the earth's surface and the temperature of the layer where, from tephigram data, the crystal was estimated to be formed. The results are in good agreement with our laboratory data, as shown by Figure 5. The agreement was not only qualitative, but the numerical temperature values also showed good coincidence. His results do not agree well with those obtained by aufm Kampe, Weickmann, and Kelly (1951), whose experiment dealt with ice crystals made by seeding. Conditions of formation may be different for snow and ice crystals, and Gold's results show that this sort of study must use data for snow crystals, not ice crystals.

SHAPE OF ICE CRYSTALS AND CONDITIONS OF FORMATION

The shape of natural ice crystals has been studied in few examples. The shape of crystals obtained by seeding was studied by Schaefer (1949), and more in detail by aufm Kampe, Weickmann, and Kelly (1951). In the latter investigations, the shape of ice crystals obtained at water saturation was studied as a function of temperature. A supercooled cloud was produced by introducing steam into a cold chamber at various temperatures. Ice crystals were made by seeding this supercooled cloud, and their shape examined under a microscope.

Various shapes were found: transparent hexagonal plates, several kinds of prisms, hexagonal plates with ribs, double plates, double stars, dendritic forms, spatial aggregates of plates, and more complicated figures. Except for the transparent plates and the aggregates of crystals, all these shapes can be considered as variations of a hexagonal prism, which we consider to be a fundamental form of ice crystal. Figure 6(a) is a photomicrograph of this form of crystal, made in the cold chamber at –22°C, and at a moderate supersaturation. The plan and elevation are shown schematically in Figure 6(b).

Variations of this prism are shown in Figure 7. Figure 7(1) is a typical form. When this type decreases in thickness, it becomes a thin plate with a hexagonal pattern, called "plate with ribs" (3). Figure 7(2) is the intermediate stage. The hexagonal pattern seen in most of the hexagonal plates is the result of the skeleton development. In a fairly thin plate, this pattern is due to the hollow spaces formed by the skeleton development, Figure 8 shows one good example, a crystal of the sector type made with T_a at –13°C and an ample supply of water vapor. The characteristic pattern seen in Figure 8(a) is due to the narrow spaces between two layers which form this sector. An oblique view (Fig. 8(b)) shows the double-sheet structure clearly. When the crystal grows chiefly along the principal axis of crystallization, it becomes a needle with a hollow on each of the ends like the kick in a glass bottle (Fig. 7(4)).

The skeleton structure develops also on the tips of branches of dendritic crystals. Tips of branches are classified, excluding the pointed

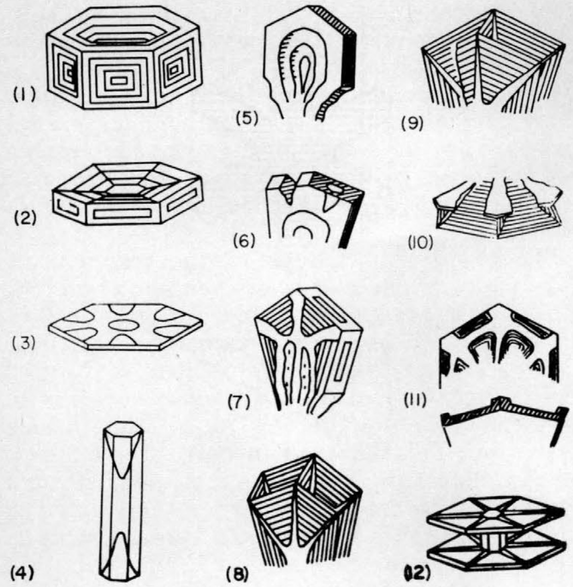


FIGURE 7. VARIATIONS OF A PRISM WITH HEXAGONAL SKELETON STRUCTURE
(1) Typical form; (2) Intermediate form between (1) and (3); (3) Plate with ribs; (4) Needle; (5)-(11) forms of tips of branches of dendritic crystals; (12) miniature capped column (double-plates crystal).

ones, into seven forms, shown in (5) - (11) of Figure 7. Type (5), a thick plate almost without hollows on the sides, is often observed in slowly formed crystals. Though no hollow is seen on its sides, it has a slight depression on its base, a remnant characteristic of the skeleton structure. Type (6) is similar, with small cavities opening on its sides, some of which often form a notch as shown in the sketch. Type (7) has a structure similar to that of the thick plate (2). With larger hollows and less ice substance, this type of crystal becomes type (8). Viewed from the side, this crystal appears to be a rectangular box. Rectangular crystals of ice are found on rare occasions both in natural frost and in artificial snow, but most of such "rectangular" crystals seem to belong to type (8).

When the supply of water vapor decreases, a part of the base planes of (8) is often undeveloped, resulting in the form sketched in (9). If this tendency is intensified, only one of the base planes is fully developed, with the remnants of the other plane as seen in (10). If this tendency continues, the second plane completely disappears and the crystal becomes a plane with ridges running on it (11). Classifying the abundant varieties of skeleton structure explains most of the complexity of types of ice and snow crystals. For instance, the miniature capped column (Fig. 7(12)), which is one type of initial stage of snow crystals, can be regarded as a specially developed skeleton. This crystal is called double plates by aufm Kampe, Weickmann, and Kelly (1951). This double-plates crystal is very rarely observed in nature, but can be produced in the laboratory without much difficulty.

In many cases, close observation of dendritic snow crystals shows the existence of a small hexagonal plate at the center (Fig. 1a; Fig. 9a), not on the same plane as the dendritic crystal but a little above it. Snow crystals with this central hexagonal plate comprise a considerable percentage of the dendritic crystals observable in nature, and are formed only when one of the planes of double plates or

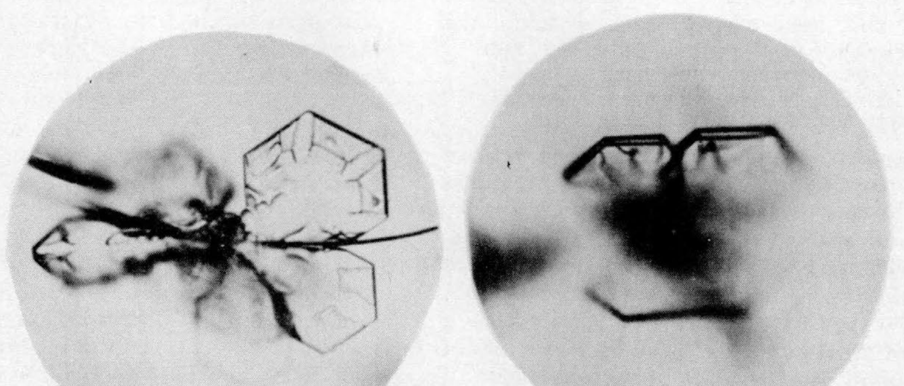
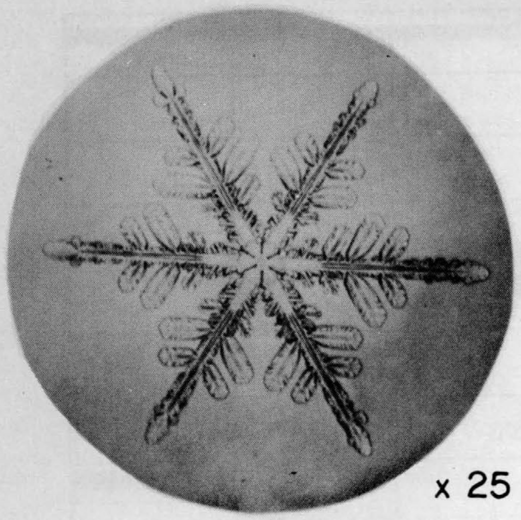


FIGURE 8. CRYSTAL WITH DOUBLE-SHEETS STRUCTURE
(a) Characteristic pattern of the branch; (b) Oblique view of (a).



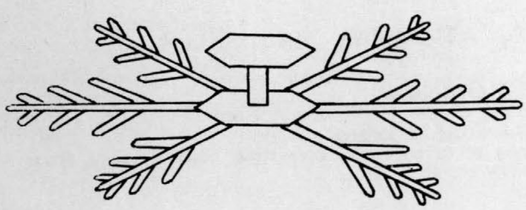


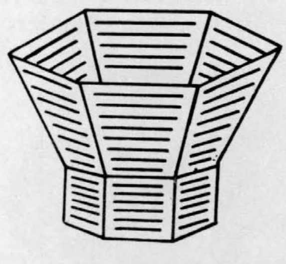
FIGURE 9. DENDRITIC CRYSTAL WITH A SMALL PLATE AT THE CENTER
(b) is the sketch of a crystal similar to (a)

miniature capped column develops to full extent (Fig. 9b). Therefore, the double-plate ice crystal must not be rare as the initial stage of snow crystal.

Figure 10(a) shows what is called a cup crystal. This type is often seen among depth hoar, and it can be made in the laboratory without difficulty, but a well developed cup is very rare among snow crystals, and we could only get one photograph. However, it is often observed that a portion of the snow crystal tends to grow into cup form. Among ice crystals obtained by seeding, this type is not observed because it represents the stage subsequent to the germ. This form results when a skeleton prism develops both along the principal axis and on the base plane of crystallization. If the skeleton prism grows chiefly on the base plane, it becomes a shallow dish or hexagonal plate (Fig. 10b). The lines from the center toward the corners of the plate correspond to the ridges in Figure 7(11); here, the ridges are running on the back side of the dish. Development of this snow crystal form is thus explained by considering the germ or ice crystal as a variation of a skeleton prism.

Figure 11 compares conditions of formation of ice crystals and snow crystals. The general tendency is the same, but transparent plates are not seen in snow crystals and irregular needles and cup crystals are not observed in ice crystals.

The origin and nature of the transparent plate which is produced between about −0.5°C and −4.5°C are not clarified yet, but it is a corresponding form to a discoid or circular transparent crystal of ice, which is formed when slightly supercooled water begins to freeze, and is one type of initial stage of ice formation. This discoid is usually about 2 or 3 mm in diameter and rarely exceeds 5 mm. When the discoid grows larger than about 5 mm, six branches extend out, transforming it into a hexagonal crystal with a circular area at the center. The fact that the transparent plate is not observed among snow crystals concords with its being an ice formation made by freezing of water. Photomicrographs of natural snow crystals show many crystals with transparent portions at the center. This transparent portion may be circular (Fig. 12) or hexagonal, which is the next stage of the discoid (Fig. 1b). From these occurrences, it is quite natural to suppose that transparent hexagonal as well as circular plates are formed as the initial stage of natural snow crystals. The nature of the transparent plate formed in



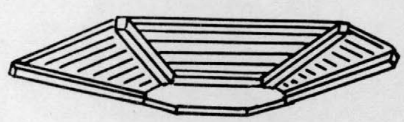


FIGURE 10. SOME MODES OF SNOW-CRYSTAL GROWTH
(a) Cup crystal; (b) Dish-shaped crystal.

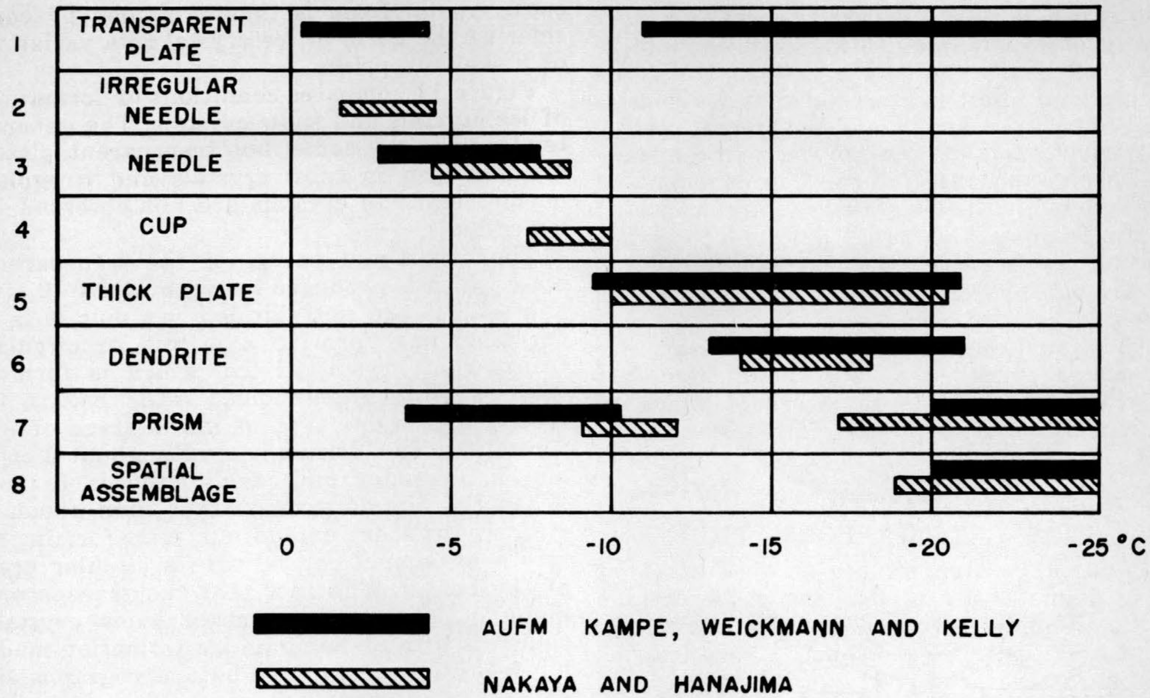


FIGURE 11. CONDITIONS OF FORMATION OF SNOW AND ICE CRYSTALS
Black bands, from aufm Kampe, Weickmann, and Kelly (1951), show occurrence of ice crystals. Shaded bands, from Nakaya (1933-38) and Hanajima (1942-45), show occurrence of snow crystals.

the air and of the discoid in the water are both unknown at present, and need future investigation.

Among ice crystals formed by seeding, prisms are reported to occur at higher temperatures than hitherto considered, between —4°C and —10°C. This range roughly coincides with that of the needle and cup forms of snow crystal. The needle crystal of snow is usually a bundle of component needles. If we examine the structure closely, we find that each component needle is also an assemblage of many prisms. One example is shown in Figure 13(a). In our experience in Japan, a

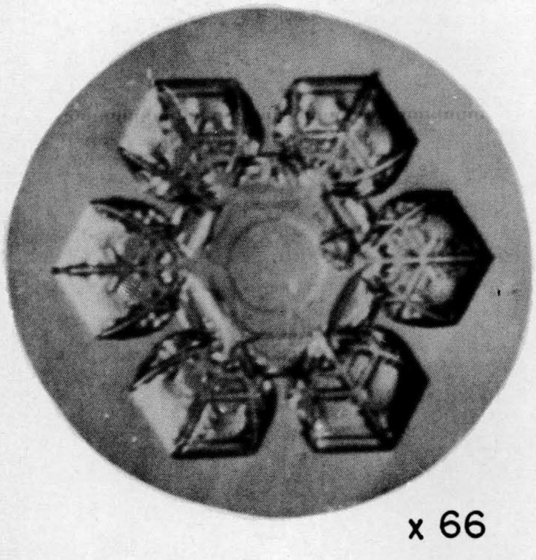


FIGURE 12. SNOW CRYSTAL SHOWING DISCOIDLIKE STAGE AT THE CENTER
(From Hanajima, 1942-45).

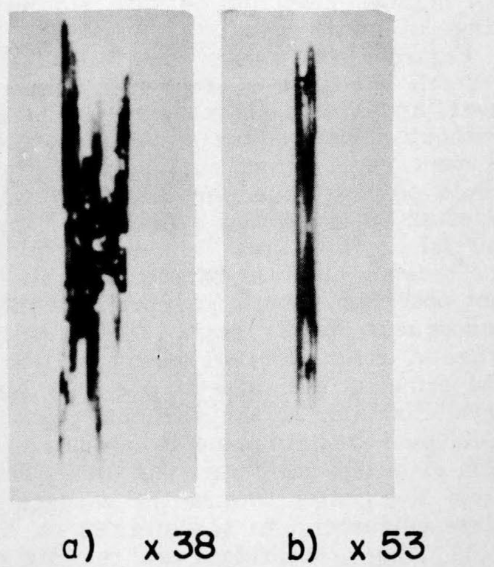


FIGURE 13. NEEDLE CRYSTALS OF SNOW
(a) Combination of component needles; (b) Elementary needle.

single needle is very rarely observed; only one photograph was obtained in about 10 years of observation (Fig. 13b). Thus, the ordinary needle snow crystal may be considered to be an assemblage of ice crystal prisms. This view explains one apparent discrepancy between conditions of formation of snow and ice crystals. Needle crystals are reported (aufm Kampe, *et al.*, 1951) among ice crystals formed by seeding, but no photograph is shown nor any explanation of its structure given.

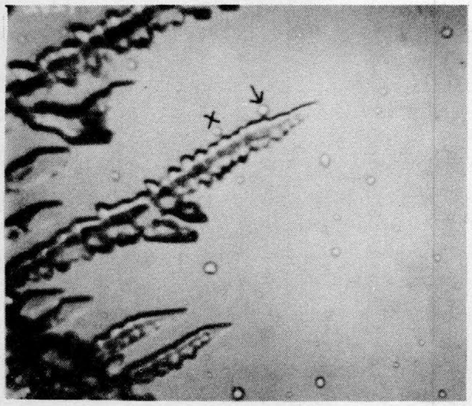
The conditions under which crystals are formed in the air are very complicated, but they are explained to some extent when we treat ice crystals separately from snow crystals.

MECHANISM OF SNOW-CRYSTAL FORMATION

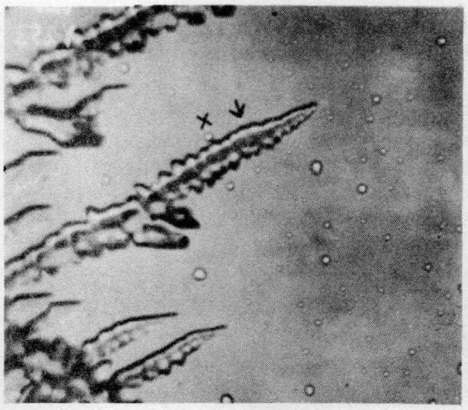
In our apparatus, minute droplets of about 1μ in diameter are almost always observable in the air under the conditions for snow-crystal formation. They do not freeze to the crystal in the form of droplets, but suddenly disappear at the moment of contact with the crystal, as if the water molecules of the droplet spread on the surface of ice.

This phenomenon is more easily observed in window hoar, the ice crystals formed on a window pane by "sublimation." In most cases, the glass surface was previously covered with numerous supercooled droplets, and the hoar crystal develops through the field of scattered droplets. When a tip of the crystal approaches them, most of the droplets vanish or diminish their size markedly by evaporation caused by the vapor-pressure difference of ice and water. Often, however, some remaining minute droplets are caught by the streamer of hoar crystals. A droplet in this case, as in the case of snow, does not freeze to the crystal in the form of a droplet, but appears to spread on the crystal surface. This phenomenon was studied by Yosida (1940). Two photomicrographs are reproduced in Figure 14. In Figure 14(a), the droplet marked by an arrow still remains as a water droplet, although it is nearly touched by the ice crystal. At the moment it is touched completely by the crystal (Fig. 14b), the droplet suddenly disappears, while the other marked by x still remains, but also disappears in the next stage. With hoar crystals, this phenomenon occurs for larger droplets than with snow crystals. In this example, the diameter of the droplet is about 14μ.

This phenomenon may be explained by the sudden evaporation of the droplet; aufm Kampe, Weickmann, and Kedesdy (1952) suggest that a droplet of 1μ in diameter can evaporate at −10°C within 0.7 second at water saturation. But there is another possible explanation: the surface diffusion of H_2O molecules on the surface of ice crystals. Many investigators believe that this surface diffusion takes place, similar to that shown for growing mercury crystals by Volmer and Estermann (1921). De Quervain (1945) tried to confirm this phenomenon by keeping a crystal of snow in paraffin oil at −5°C, so that he could observe the deformation in its shape, but this experiment cannot establish the fact, as the water solubility of paraffin oil was not considered. The surface nature of ice crystals, a problem since the days of Faraday and Tyndall, was recently treated by Weyl (1951) who suggested the existence of a "liquid"



a) x 78



b) x 78

FIGURE 14. GROWTH OF A HOAR CRYSTAL
(b) is the next stage of (a). From Yosida (1940).

water film on the ice surface. The metamorphism of crystals in the snow cover, the mechanism of hardening of snow, and allied phenomena are also considered to be the result of the behavior of molecules on the surface layer of ice. We are now inclined to attribute the sudden disappearance of a minute droplet on contact with ice surface to the surface diffusion of H_2O molecules, although this diffusion itself is not well established experimentally[2].

An apparatus was designed to detect the effect of removing these minute droplets from the upward air current. The inner cylinder of glass in our snow-making apparatus was replaced by a brass cylinder, and a thin wire was stretched through the cylinder. The brass cylinder and the wire were connected to a high tension source, and the droplets removed from the upward air current by the well known Cottrell method. The preliminary experiment was carried out in the laboratory of Hokkaido University. The growth of dendritic crystals stopped when these droplets were removed, the value of s having come down about 20 percent, for example, from 125 to 105 percent. The experiments are now being carried on, and a detailed report will be published in the near future.

The delicate structure and design of snow crystals are due to their sharp edges and minute ridges. It is easily shown that these edges and ridges are transformed into a more rounded form at a temperature below freezing, even if the crystal is kept in air slightly supersaturated with respect to ice. Warm water vapor is sent into a bottle at low temperature, and frost crystals made all over the inside of this bottle. When the bottle is closed, the air inside must be slightly supersaturated with respect to the plane surface of ice, because the whole space is surrounded by crystalline frosts with pointed edges. A snow crystal of fine dendritic shape is hung from the cap of this closed bottle by a thin filament and left at a low temperature, say $-10°C$. Under these circumstances, the crystal undergoes a sensible sublimation metamorphism in a few hours, and we cannot keep its original shape and structure. Even for keeping the original form, we need more supersaturation. So it is not surprising that such high values of s are necessary, as shown in Figure 2, for the growth of this sort of crystal.

CONCLUSION

Measurement of total water content in the air where snow is formed showed that most snow crystals are formed in the range above water saturation. The excessive water was found to exist in the form of minute droplets of about 1μ in diameter which behave like water vapor in the process of condensation. The term "supersaturation" as used in this article means the total water content, and the condensation of these minute droplets is included in the term "sublimation," which essentially means the condensation of vapor only.

The foregoing descriptions are founded on our knowledge of artificial snow crystals only, but we hope to extend our work to show that a similar mechanism takes place in the formation of snow crystals in nature. This idea is supported by Kumai's investigations on snow crystal nuclei (1951). By the use of an electron microscope, he found almost always a relatively large solid nucleus at the center of snow crystals. Besides this nucleus, which is of the order of 1μ in size and is regarded as the nucleus of the snow-crystal germ, he found numerous condensation nuclei of much smaller size; the mean diameter measured about 0.1μ. An electron photomicrograph of any portion of various snow crystals was full of these condensation nuclei. The mean concentration of these condensation nuclei per unit area of crystal is roughly 100 per μ^2 for thicker crystals, and 10 per μ^2 for thinner ones. This value coincides roughly with the assumed number of droplets making up the crystal. We consider that these minute droplets play an important role in snow-crystal growth. The difficulty is that we do not know whether such minute droplets exist abundantly in the natural atmosphere. Up to the present, such minute droplets have not been found in natural clouds, as pointed out by Weickmann in his comment on Kumai's paper. However, this does not mean that they do not exist, since present techniques cannot catch droplets of this size[3]. Precise determination of droplet distribution in clouds will answer this question.

One important problem left untouched is the formation of some crystals in the range between water and ice saturations (Fig. 2), Especially the fact that dendritic growth extends below the curve of water saturation

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[2] The report of a simple experiment showing the existence of a "liquid film" on the surface of ice has been published as SIPRE Research Paper 4.

[3] Dessens (1949) observed minute droplets of 1μ or less in diameter by the use of spiders' threads as the collector, but it was in fine-weather conditions.

seems contradictory to our theory. We consider, however, that cloud formation can take place even in these conditions. Through inconceivable in an equilibrium state, measurements of humidity in growing cloud or fog often show values less than 100 percent. It is not rare that humidity in a fog comes down to 90 percent or less. The lower limit of dendritic growth is 93 percent (Fig. 3). If the humidity is 90 percent in this case, the difference of 3 percent will mean that 1 x 10^5 droplets of 1μ in diameter must exist in 1 cm^3 of the air.

As yet, we know very little about the formation of snow crystals. For use in our study of the subject, the author suggests the differentiation between snow crystals and ice crystals, and presents, as a working hypothesis, the new theory of the role of minute droplets in snow-crystal formation.

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