Classification of Snow Flakes and their Structures

By

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Abstract

Many snow flakes were photographed between 1951 and 1954 in Japan, and they were classified, according to the purposes by three methods, their metamorphic stages, shapes in falling state, and crystal habits.

It was observed that the snow flakes change their crystal states in the process similar to that of the fallen snow. Considering aerodynamically the shape and velocity of snow flakes in falling state, a clue for presuming the uniformity of crystal habit in snow flakes was acquired. In the photographs of snow flakes obtained hitherto, it was found that in all types of snow crystals is formed one snow flake with the same type only, while another with almost all combinations between the different types is formed. All the ways of contact geometrically possible, namely, point, line, intertwined, and irregular contact were found in the snow flakes. The top of branch of dendritic crystals plays a leading role in the adhesion mechanism between the crystals.

From those results, it was presumed that the large snow flakes might be composed of snow crystals of dendritic type.

§ 1. Introduction

Recently, some attentions have been payed to the snow flakes from the points of view that the snow flakes are considered to be the origin of large raindrops, and to correspond to the hydrometeors in the bright band of radar echo.

Seligman referred briefly to the manner of clinging between snow crystals in his "Snow Structure and Ski Field". Many photographs of snow flakes were lately recorded in Nakaya's "Snow Crystals" which was very useful to our work. Mason described that the snow flakes originate from horizontal collisions between snow crystals during fall. One of the authors showed by calculations that a large snow flake could be formed by its vertical collisions with snow crystals due to the difference between their falling velocities.

Although theoretical considerations have not been yet made, it appears

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that the snow flakes are formed near the freezing level, and the snow crystals of dendritic type are easy to form the large snow flake. In order to investigate the snow flake systematically, it may be necessary to act on the results of numerous observations. With this aid, we have gathered as many photographs as possible in recent four seasons in Northern Japan, and arranged them on the basis of their structures for the next process of investigations in this field.

§ 2. Classifications of snow flakes

According to the purposes, snow flakes were classified by three methods, that is, their metamorphic stages, shapes in falling states, and the crystal type of snow crystals which occupy the majority of the snow flakes.

a) Classification by metamorphic stages.

Fresh snow flakes suffer various changes in their falling states, to say, rimed by supercooled cloud particles, granulated by sublimation or refreezing, and wet by partially melting, since then melted into raindrops at a warm climate. The changes correspond to those of fallen snow which Saito\(^5\) classified by their metamorphic stages. Our classifications of snow flakes are, therefore, more or less similar to that of Saito, as stated later. The snow flakes at each stages are shown in Pl. I.

Fresh snow flakes (Photos. 1~3, Pl. I). In a cold climate, one may observe snow flakes whose snow crystals do not suffer remarkable changes yet and hold fine structures in their branches or connecting parts. This is the initial stage of the snow flakes. We call them in this stage “Fresh snow flakes”, neglecting a few cloud particles attached on the snow crystals, because it is rare near the earth’s surface that snow crystals carry no cloud particles.

Rimed snow flakes (Photos. 4~6, Pl. I). Such snow flakes that are covered by numerous cloud particles, we call “Rimed snow flakes”, although it is unclear that after forming the snow flakes the particles have attached to or initially rimed crystals have clinged mutually.

Granulated snow flakes (Photos. 7~9, Pl. I). When a snow flake falls into an atmospheric layer of relatively low equilibrium vapor pressure, rapid sublimation takes place, and the snow flake loses the fine structures in its snow crystals. At the lower layer, individual crystals of the snow flake undergo also melting and refreezing partially. Owing to those effects, the crystals tend to be granulated. This is the second stage of the snow flake.

Wet snow flakes (Photos. 10~12, Pl. I). When a snow flake is considerably wet, it shrinks undoubtedly but does not become always one block. In the case of Photo. 11, the snow flake has been separated to three parts. Considering that the snow flakes are constantly subjected to the resistance from air in the vicinity during fall due to their large falling velocities and complicated
shapes, it is supposed that snow flakes would be disrupted into a few raindrops before melting perfectly.

Melted snow flakes (Photos. 13–15, Pl. I). This is the final stage of snow flakes. In sleety weather, a piece of ice unmelted yet is detected within a raindrop, although this ice piece is often overlooked. Photos. 13–15 show such pieces contained in raindrops by which some splashes were raised, as seen in those figures obtained by photographic paper method.6)

b) Classification by shapes of snow flakes during fall.

It is our opinion that the snow flake in falling state should be more watched, because the name "snow flake" is given to the snow during fall. From this point of view, we classified the snow flakes by their shapes while falling, as follows.

Horizontal type (Photos. 16 and 17, Pl. II). It is aerodynamically stable that a body of plate type or a pole type with a uniform density, falls keeping its plane or axis horizontally. Taking an analogy with this phenomena, we presume that such a snow flake that keeps its plane or axis horizontally during fall, may be composed of uniform snow crystals, in other words, have a uniform density. For examples, Photo. 16 shows a snow flake of horizontal type formed of uniform dendrites, and Photo. 17 represents that of two stellar crystals. It is considered that the snow flake of this type has a larger probability of touching mutually than those of other types, because the former occupies a wider cross-section than the later and falls slowly, that is, floats for a long time in the air.

Vertical type (Photos. 20 and 21, Pl. II). If one end of a snow flake is extremely dense, the snow flake falls keeping its heavier part downward and fluttering its lighter one. Photos. 20 and 21 are the examples of this type. These snow flakes are composed of a graupel and a stellar crystal which are considered to have clinged mutually owing to the difference between their fall velocities. From observations,4) it was found that the snow flake of vertical type has larger fall velocity than that of horizontal type.

Inverted cone type (Photos. 18 and 19, Pl. II). The snow flake of this type is situated between those of horizontal and vertical type. During fall, the relatively heavier part of the snow flake occupies the downward of the cone, and an end of the lighter one plays a rudder with a constant angle. At the result of the rudder, the snow flake of this type falls rotating spirally. One may see the rotating motion and the compact part at the downward of inverted cone in Photos. 18 and 19.

c) Classification by crystal types.

In our observations, it was found that all kinds of snow crystals except sleet, form snow flakes so we classified also the snow flakes by the classification of crystal type of component snow crystals for practical purposes by the International Commission of Snow and Ice. After this, we shall repre-
sent the type of a snow flake according to that of snow crystals which occupy the majority of the snow flake. Sleets (refrozen ice pellets) are scarcely observed in our country, and it is not likely that they form snow flakes. Observed snow flakes are tabulated in Pls. III and IV, and the explanations of each photographs are given in the opposite pages of the corresponding plates.

The base of the snow crystal of columnar type shown in Photos. 22, 23, and 24 have grown somewhat horizontally, namely, have approached to capped columns. We think that pure columns do not form recklessly snow flakes, although crystals of bullet type make cling one another at their tops as described in “Snow Crystal,” p. 426.

The classifications described above are tabulated in Table 1.

Table 1.
Classifications of snow flakes.

<table>
<thead>
<tr>
<th>Methods of classification</th>
<th>Term</th>
<th>Code</th>
<th>Photo. no.</th>
<th>Pl. no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphic stage</td>
<td>fresh snow flake</td>
<td>O</td>
<td>1-3</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>rimed &quot;n&quot;</td>
<td>∞</td>
<td>4-6</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>granulated &quot;n&quot;</td>
<td>∞</td>
<td>7-9</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>wet &quot;n&quot;</td>
<td>∞</td>
<td>10-12</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>melted &quot;n&quot;</td>
<td>∞</td>
<td>13-15</td>
<td>I</td>
</tr>
<tr>
<td>Shape in falling state</td>
<td>horizontal type</td>
<td>°</td>
<td>16, 17</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>inverted cone &quot;n&quot;</td>
<td>∨</td>
<td>18, 19</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>vertical &quot;n&quot;</td>
<td>0</td>
<td>20, 21</td>
<td>II</td>
</tr>
<tr>
<td>Crystal type</td>
<td>columns</td>
<td></td>
<td>22, 23</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>plates</td>
<td></td>
<td>25, 26</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>stellar type</td>
<td></td>
<td>28-30</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>spatial dendrites</td>
<td></td>
<td>31, 32</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>capped columns</td>
<td></td>
<td>34, 35</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td>needles</td>
<td></td>
<td>37, 38</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td>graupel</td>
<td></td>
<td>40, 41</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td>irregular crystals</td>
<td></td>
<td>43, 44</td>
<td>IV</td>
</tr>
</tbody>
</table>

§ 3. Combination between snow crystals of different types

Snow crystals of different types are often observed at a same time, and those of each types must have various falling velocities respectively. If the snow flake is formed by the collision with the snow crystals owing to the difference between their fall velocities, it is probable that a snow flake collides more frequently with the crystals of other type than with those of same one. And it is suggested that in a snow flake, a component snow crystal of a larger
fall velocity might grow at a higher atmospheric layer than the layer at which the other crystal of smaller velocity. In the fact, the snow flakes composed of various combinations between different types were observed as shown in the last columns of Pls. III and IV. For the simplicity, we selected only the combinations between two different types which are graphically shown in Fig. 1. The thickness of the lines which combine two types, represents the frequency of occurrence determined by our photographic observations. Therefore, the frequency does not necessary to show the grade of the inclination of clinging between the types, but perhaps mean the frequency of occurrence of the snow crystals. This conception is supported by the fact that the frequency of snow flakes agrees with that of individual snow crystals.

<table>
<thead>
<tr>
<th>Types of snow crystals composing snow flakes</th>
<th>Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td></td>
</tr>
<tr>
<td>Plates</td>
<td></td>
</tr>
<tr>
<td>Stellar type (sector form)</td>
<td></td>
</tr>
<tr>
<td>Spatial dendrites (radiating type)</td>
<td></td>
</tr>
<tr>
<td>Capped columns</td>
<td></td>
</tr>
<tr>
<td>Needles</td>
<td></td>
</tr>
<tr>
<td>Rimed crystals (thick plates, graupel-like crystals)</td>
<td></td>
</tr>
<tr>
<td>Graupel</td>
<td></td>
</tr>
<tr>
<td>Irregular crystals</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1
The meteorological conditions for the growth of various crystal types are shown in Table 2. It is naturally expected that snow crystals which grew at similar air conditions may form a snow flake, but it is remarkable that as shown in Photos. 20 and 42, a stellar crystal clings to a graupel whose conditions for growth is considered to be far different from that of stellar type. Such a snow flake might originate from the difference of fall velocity between the two crystals. One sees in Fig. 1 that the snow crystals of irregular type combine with almost all types of crystals. This may be caused by the following facts; it is often difficult to discriminate the crystal type, therefore, the unclear crystals tend to be regarded as of irregular type, and the crystals of this type fall more frequently than is expected generally.

Table 2.

<table>
<thead>
<tr>
<th>Crystal type</th>
<th>Air temperature (°C)</th>
<th>Vapor supply</th>
<th>Falling velocity (m·sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needles</td>
<td>1-4</td>
<td>little</td>
<td>0.3-0.6</td>
</tr>
<tr>
<td>Irregular needles</td>
<td>4-7</td>
<td>little</td>
<td>1.1</td>
</tr>
<tr>
<td>Columns</td>
<td>9-12, 17-21</td>
<td>much</td>
<td>0.3-0.6</td>
</tr>
<tr>
<td>Plates, sectors</td>
<td>11-14, 17-21</td>
<td>with cloud particles</td>
<td>0.6-1.8</td>
</tr>
<tr>
<td>Dendrites (stellar, spatial)</td>
<td>14-17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimed crystals (thick plate)</td>
<td>9-14, 17-19</td>
<td>with cloud particles</td>
<td>0.6-1.8</td>
</tr>
<tr>
<td>Graupellike crystals</td>
<td>relatively warm</td>
<td>with cloud particles</td>
<td>1-2.5</td>
</tr>
<tr>
<td>Graupel</td>
<td></td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Irregular crystals</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

§4 Manners of contact between snow crystals

We classified geometrically the manners of contact or clinging between two snow crystals as follows, point contact, line contact, plane contact, intertwined contact, and irregular contact. These manners of contact were more finely classified as shown in Fig. 2 in which typical examples are sketched from corresponding photographs. Such assemblage of snow crystals that are considered to have originated from the attachment of the nuclei i.e. twelve sided crystal or combination of bullet type gathering at heads each, were excluded from the snow flake.

a) Point contact.

This manner of contact is more classified to point-point, point-line, and point-plane contact.

Point-point (Photos. 46–51, Pl. V). Almost all dendritic crystals cling to one another at the ends of their branches. The examples are shown in
<table>
<thead>
<tr>
<th>Manner of Contacts between Snow Crystals</th>
<th>Point contact</th>
<th>Line contact</th>
<th>Plane contact</th>
<th>Intertwined contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-point</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point-line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line-plane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line-line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2
Photos. 46–51, and their explanations are given in the opposite page of the Pl. V. Frequently, crystals of stellar type cling spatially one another, thus, a very light snow flake can be formed from the stellar crystals, although the individual crystals are not so light. Some times, a large dendritic crystal of plane type carries many small crystals at the ends of its branches, and becomes often the center of a snow flake. See Photo. 50. Rarely two snow crystals cling mutually with such a manner that the direction of the branches of both crystals are parallel as seen in Photos. 48 and 51.

Point-line (Photos. 39 and 35). Some rimed irregular crystals cling to fine needle crystals with point contacts.

b) *Line contact.*

Line-line (Photo. 25, Pl. III). Such crystals as plates or columns which grow at the condition of low super-saturation vapor pressure cling rarely at their edges.

Line-plane (Photos. 22 and 23, Pl. III, Photo. 34, Pl. IV). Deformed columns are inclined to cling to one another with this manners of contact.

c) *Plane contact.*

Snow flakes composed of stellar crystals which were piled up each other, were not so frequently observed as is expected. The snow crystals shown in Photos. 28–30, Pl. III are apparently piled up one another, that is, touched with the plane contact, but they might contact mutually at the fine points on their surfaces.

d) *Intertwined contact.*

Snow crystals intertwined as sketched in Fig. 2 are described in “Snow Crystals,” p. 277. It is likely that these intertwined crystals gathered each other at a half way of their crystal growth, because it is not expected that these two stellar crystals intertwined by accident, leaving a especially strong adhesion power at the ends of the branches. This adhesion power will be stated later.

e) *Irregular contact.*

Snow crystals included in large snow flakes contact irregularly by mutual mechanical pressure.

§ 5. The adhesion power between snow crystals, forming a snow flake

As described above, it is almost all at the ends of branches or tops of cones that snow crystals cling to one another. Because the ends of tops are situated at the most outer parts of snow crystals, it would be natural that snow crystals cling often at those parts if they contact mutually.

But on the strong adhesion power at the fine parts, we think, some problems are still left. It is surprising that a graupel of large fall velocity holds
still the touch with a fine dendrite during fall.

When two fine points of branches contact with each other, the point would melt temporarily owing to the mechanical pressure or frictional heat. Then a strong bridge may be formed in the place by sublimation phenomena, as shown in Photo. 52, Pl. V, because the contacting part have very large curvature.

In the case, snow crystals lose their fine structures and become round with the progress of sublimation, as Saito$^5$ and Kojima$^7$ pointed out in fallen snow. Cloud particles which froze to the surface of a crystal would play also this fine connecting role. On the other hand, some snow flakes which contain rimed snow crystals are fragile when received on the ground. Photos. 53 and 54, Pl. V show the fragments from such a fragile snow flake respectively. It is also considered that Coulomb's force between snow crystals charged at opposite signs, has some effect on the adhesion power. As the electrostatic charge is localized to the corners of snow crystals, Coulomb's force would be particularly strong at these places. The graupel which is formed of numerous cloud particles are considered to be charged negatively by Workman-Reynolds' effect.$^8$ While, it was found by many observers$^9$ that the charge on snow is more often positive than negative. Therefore, Coulomb's force will probably play a main role in connecting the graupel and stellar crystal.

§ 6. Large snow flakes

Such a large snow flake that is composed of thousands crystals, we think, would have grown under following circumstances.

i) The larger the concerned space density of snow crystals is, the more often the crystals will collide mutually. From the calculations by the one of the authors,$^4$ the volume of the snow flakes is proportional to the third power of the space density of the crystals in the air. The condition on which the rate of the crystal growth is largest, ranges from $-14$ to $-17^\circ$C, because the difference of saturation vapor pressure between super-cooled water and ice is most in the range. This temperature range agrees with that of the condition on which snow crystals grow to the dendritic form.

ii) As the snow crystal or flake of dendritic type is very light, in other words, has a large volume per one crystal or flake, its chance for the mutual collision of this type may be more than of other types.

iii) The falling velocity of dendritic snow flake is small, that is, the snow flake of this type floats in the air for a longer time than of other types. Therefore it has the largest frequency of collision with snow crystals in all types. The snow flakes of high fall speed can not grow largely, as described in § 2.
iv) It is considered that the snow flake begin to be form at about -10°C level. From this point of view, the snow crystals of dendritic type which grow at -15°C level, are favorable to a wide mutual collision layer, compared with those of other types which grow at the warmer i.e. lower level.

v) As described previously, the dendritic snow crystals have many branches which have a strong adhesion power.

vi) A calm weather and relatively warm climate near 0°C are necessary for the large snow flake growth, of course.

Considering these reasons for snow flake's growth, the large snow flakes must be of dendritic type, and of horizontal one, because the snow flakes of vertical or inverted cone-type can not grow largely due to their high fall speed. The large snow flakes shown in Photos. 55~57, Pl. V support our opinion.

Acknowledgements

We projected this work from Prof. Nakaya's "Snow Crystals" which played a leading role in our work, as quoted often in this paper. We express their best thanks to Mr. M. Shōda, the head of Snow Institute at Shiozawa, and to members of Nakaya Laboratory of Hokkaido University who gave us the conveniences for the observation, especially to Mr. K. Higuchi who allowed us to publish his photographs of snow flake. We thank also to B. Arai and T. Nakayama for their cooperations.
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References

7) Kojima, K., 1952: Change in shape of snow crystals, II. Low Temperature Science 9, 187-203.
Explanations of Plate I

Metamorphic stages of snow flakes.

Photo. 1. ×5 Fresh snow flake.
Photo. 2. ×4.3... “... “
Photo. 3. ×7.7... “... “
Photo. 4. ×8.8 Rimed snow flake.
Photo. 5. ×3.9... “... “
Photo. 6. ×7.2... “... “
Photo. 7. ×4 Granulated snow flake.
Photo. 8. ×2.5... “... “
Photo. 9. ×2.7... “... “
Photo. 10. ×3.3 Wet snow flakes.
Photo. 11. ×1.6 Wet snow flake.
Photo. 12. ×2.3... “... “
Photo. 13, 14 and 15. ×1.3 Melted snow flakes and rain drops obtained by “photographic paper method”.
Explanations of Plate II

Side views of snow flakes while falling, photographed by successive electric sparks.

Photo. 16.  ×2.1 A snow flake of horizontal type, being fluttered.
Photo. 17.  ×2.3 A snow flake of horizontal type, composed of two stellar crystals.
Photo. 18.  ×1.2 A snow flake of inverted cone type.
Photo. 19.  ×1.5 A snow flake of inverted cone type. The lower part is more compact than the upper part.
Photo. 20.  ×1.7 A snow flake of vertical type, composed of a stellar crystal and a graupel.
Photo. 21.  ×2 A snow flake of vertical type.
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Plate II

Vertical type

Inverted cone type

Horizontal type

Photo. 17

Photo. 18

Photo. 19

Photo. 20

Photo. 21
Explanations of Plate III

Types of snow crystals, composing snow flakes.

Photo. 22. ×14 Assemblege of columns; irregular contact.
Photo. 23. ×11 Three columns-plate; line contact.
Photo. 24. ×15 Column-plate; point contact.
Photo. 25. ×23 Plate-plate; line contact.
Photo. 26. ×24 Plate-plate; point contact.
Photo. 27. ×15 Plate-column; point contact.
Photo. 28. ×5.8 Two dendritic crystals of plane type-stellar crystal; piled up contact.
Photo. 29. ×14 Sector-sector; point contact, (Photographed by Mr. K. Higuchi).
Photo. 30. ×4.5 Three rimed crystals of plane type; piled up contact,
Photo. 31. ×4.3 Spatial dendrites-stellar type; point contacts.
Photo. 32. ×6.5 A part of a snow flake, composed of spatial (radiating) dendritites; point contacts.
Photo. 33. ×9.5 Spatial dendrite-graupel; plane contact.
Explanations of Plate IV

Type of snow crystals composing snow flake.

Photo. 34.  ×16  Capped columns; line contacts.
Photo. 35.  ×5.7  Capped columns-spatial dendrites; irregular contacts.
Photo. 36.  ×21  Capped columns-plate; line contact.
Photo. 37.  ×10.5  Needles; point contacts.
Photo. 38.  ×22  Needles; point contacts.
Photo. 39.  ×12  Needles-rimed irregular crystals; point contacts.
Photo. 40.  ×5.2  Graupel-graupel; point contact.
Photo. 41.  ×5.5  Graupel-graupel; point contacts.
Photo. 42.  ×9.5  Graupel-stellar crystal; point contacts.
Photo. 43.  ×10.5  Irregular crystals; irregular contacts.
Photo. 44.  ×9  Irregular crystals-stellar crystal irregular contacts.
Photo. 45.  ×12  Irregular crystal-needle point contact.
Explanations of Plate V

Manners of contacts between snow crystals.

Photo. 46. \( \times 14 \) Contact at an end of a branch, (photographed by Mr. K. Higuchi).
Photo. 47. \( \times 6.7 \) A small crystal, clinging to a top of a branch.
Photo. 48. \( \times 14 \) Parallel contact of branches between two crystals, clinging by one branch, (photographed by Mr. K. Higuchi).
Photo. 49. \( \times 4.4 \) Three crystals, clinging spatially by two branches each.
Photo. 50. \( \times 5.2 \) Dendritic crystal, carrying rimed crystals with it at ends of its branches.
Photo. 51. \( \times 14 \) Parallel contacts of branches between two crystals, clinging with many ends of their branches, (photographed by Mr. K. Higuchi).
Photo. 52. \( \times 8.2 \) A combining branch, thickened by sublimation.
Photo. 53. \( \times 3 \) Fragments from a snow flake.
Photo. 54. \( \times 4.3 \) Fragments from a snow flake.
Photo. 55. \( \times 1 \) A large snow flake.
Photo. 57, 58. \( \times 1,3 \) A large snow flake in which many capped columns (H-shaped) are seen.