Characteristics of Snowflake Size Distributions Connected with the Difference of Formation Mechanism

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Abstract

Observation of snowflake size distribution was carried out on the ground in order to reconsider the past observational results obtained from only a small amount of data. Based on the large quantity of data obtained in our studies, the characteristics of snowflake size distributions and their formation mechanisms are discussed.

It was found that averaged size distributions of snowflakes moved parallel to a higher number concentration, maintaining their exponential distributions with increase in snowfall intensity. These characteristics differ from those of Gunn and Marshall (1958), who reported that size distributions became broader with increase in snowfall intensity. A small variation superposed on the averaged size distribution, and changed its slope even under the condition of equal snowfall intensity. The density and riming proportion of snowflakes are shown to be the factor that determines the slope. In other words, the slope of the size distribution becomes more gentle when snowflakes have low density and are not composed of rimed snow crystals.

1. Introduction

Knowledge of the characteristics of snowflake size distributions is important for research on the growth of snow particles, cloud simulation and radar meteorology. There have been many studies on the estimation of snowfall intensity from radar measurements in the study field of snowflake size distributions. Many of these studies focused on the determination of the empirical Z-R relationship connecting between radar reflectivity factor (Z) and snowfall intensity (R) (e.g., Imai et al. 1955; Sekhon and Srivastava 1970; Yoshida 1975). In these investigations, it was tacitly assumed that snowflake size distributions were the same if snowfall intensity was equal.

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However, there have only been a few studies on the characteristics of snowflake size distributions themselves. Gunn and Marshall (1958) first reported on them. They proposed that size distributions tended to follow an exponential relationship of the form

$$N_D = N_O e^{-\lambda D}, \quad (1)$$

where D is the melted diameter of a snow particle, $N_D dD$ is the number of snow particles with a melted diameter between D and $D + dD$ in unit volume of air, N_O is the intercept, and λ the slope. They also reported that size distributions became broad, showing decrease in both the intercept (N_O) and slope (λ), with increase in snowfall intensity. However special attention should be paid to that their results were based on the 15 size distributions, with weaker snowfall intensity less than 2.5 mm/h.

Harimaya (1978) observed the size distributions of snowflakes and graupel particles, and reported their characteristics. It was found that there was a monotonic increase in the intercept (N_O), while the slope (λ) remained relatively constant as the snowfall rate increased from less than 0.1 mm/h to 0.4–0.6 mm/h. However, the slope decreased while the intercept remained relatively equal as the snowfall intensity increased from 0.4–0.6 mm/h to 1–2 mm/h. These characteristics are different from those reported by Gunn and Marshall (1958).

After that, following observational studies were reported about the actual diameter of snow particles. Houze et al. (1979) investigated the characteristics of size distributions of precipitation particles in frontal clouds, and reported that the intercept and slope of an exponential distribution above the melting level decreased with an increase in temperature (decrease in altitude). Lo and Passarelli (1982) observed the growth of snow particles in a winter storm by the following method. Starting aloft in a mesoscale precipitation area, the aircraft is placed in a constant bank angle (~15°) and a constant descent rate (~1 m/s). The aircraft spirals downward at approximately the mean falling speed of snow particles and the loops of the spiral drift with the wind. They reported that stage 1 was characterized by an increase in intercept accompanied by relatively little change in slope. Stage 2 was characterized by a rapid decrease in both intercept and slope. Stage 3 was marked by an apparent cessation of spectral evolution.

Associating with several different particle growth regions, Herzegh and Hobbs (1985) reported that sub-exponential spectra were found to be dominant in regions of weak stratiform cloud, where liquid water was scare. Exponential spectra were dominant in convective regions at the −11°C level and above, where trace amounts of liquid water were present. Super-exponential spectra were dominant in convective regions between the −1 and −9°C levels, where liquid water was present in amounts up to 0.2 g/m^3.

On the other hand, the size distributions of snowflakes were also investigated by theoretical methods. Passarelli (1978) constructed an approximate analytical model of the deposition and aggregation growth of snow in stratiform clouds. After that, Mitchell (1988) developed snow growth models in which the processes of vapor deposition and aggregation were treated analytically without neglecting changes in ice crystal habits, while the ice particle breakup process was dealt with empirically. Using this model, Mitchell (1988) was able to reproduce the observational results of Lo and Passarelli (1982).

Ikawa et al. (1991) developed a numerical model of a convective snow cloud over the Sea of Japan with a bulk parameterization scheme of cloud microphysics, which predicted not only the number concentrations of cloud ice and snow but also that of graupel, in addition to the mixing ratios of six water species. They reported that the intercept (N_O) of the size distribution obtained by simulation showed a strong dependency on the growth stage of the cloud rather than on snowfall intensity.

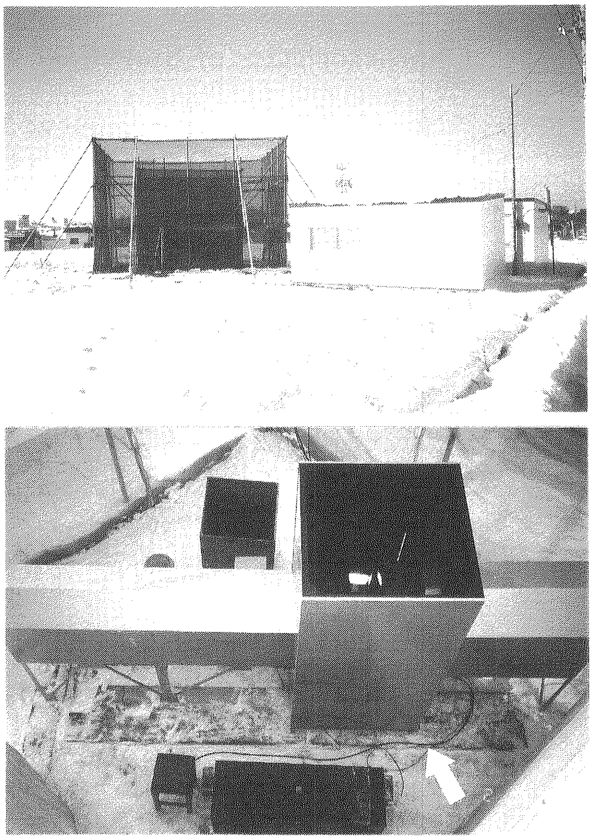

Fig. 1. Photographs of the double wind-breaker apparatus (upper photograph) and the snow particle measuring system (lower photograph). The wind-breaker apparatus consists of double nets (7 m × 7 m in horizontal scale and 5 m in height, and 4 × 4 m in horizontal scale and 4 m in height).

Due to the recent progress in electronics, observational equipment that enable a large quantity of data to be obtained is now available. Using modern electronic equipment, observation of snowflake size distribution was carried out on the ground in order to reconsider the past observational results obtained from only a few data. Based on the large quantity of data obtained, the characteristics of snowflake size distributions and their formation mechanisms are discussed in this paper.

2. Observational procedure

Observations of snowflake size distributions were carried out in Iwamizawa on Ishikari Plain, Hokkaido, Japan, from January to February, 1991. The observation site is about 40 km from the coastline along the direction of the prevailing winter-monsoon wind (Harimaya and Kanemura 1995: see Fig. 1). During an observational period, the site was under the synoptic situation of winter monsoon type, cyclone type, and mesoscale cyclone type. Snow clouds passed over the site in the ratio of about 50 % in developing and mature stages, about 50 % in the dissipating stage (Harimaya et al. 1999). Snowflake size distributions were measured by a snow particle measuring system (INTEC inc., PROSPER-10), and snowfall intensity was measured at one-minute intervals using equipment with an electro-balance and personal computer similar to that developed by Konishi et al. (1988).

For measurements of snowflake size distributions and snowfall intensity, the influence of strong winter-monsoon winds should be excluded. For this purpose, a double wind-breaker apparatus was constructed using two nets (7 m × 7 m in horizontal scale and 5 m in height, and 4 m × 4 m in horizontal scale and 4 m in height), as shown in the upper part of Fig. 1. Since snow particles fell vertically in the double wind-breaker apparatus, even when the wind in the surrounding area reached a velocity of 10 m/sec, accurate measurements of snowflake size distributions and snowfall intensity could be obtained over one-minute intervals.

The snow particle measuring system includes a CCD camera for photographing snowflakes falling in the measuring tower (arrow; 1 m × 1 m in horizontal scale and 2 m in height), as shown in the picture, lower part of Fig. 1. The images are processed with graphic information equipment and stored on a personal computer (Muramoto et al. 1993). The data stored on the computer are the size distributions of snowflakes per 0.5 mm in 1 m^3 volume of air over one-minute intervals. Space size distributions of snowflakes can be directly obtained by this system. They were formerly calculated from horizontal size distributions and the corresponding falling velocities. The falling velocity of each individual snowflake can also be simultaneously measured and recorded by this system.

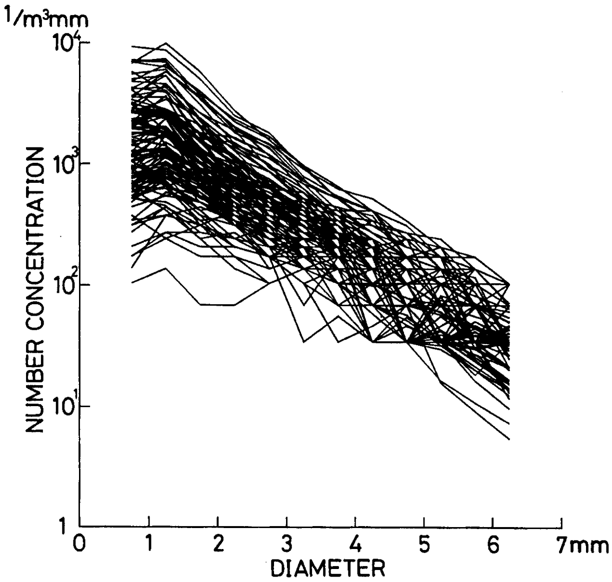

Fig. 2. A chart superposed with all of the observational data. Each solid line represents a space size distribution over a five-minute period.

Table 1. Proportion and accumulated proportion from the first to the twelfth principal components.

Principal component	Proportion (%)	Accumulated proportion(%)
1	67.6	67.6
2	15.9	83.4
3	3.5	86.9
4	3.3	90.2
5	2.6	92.8
6	2.2	95.1
7	1.8	96.8
8	1.2	98.1
9	1.0	99.1
10	0.5	99.5
11	0.3	99.8
12	0.2	100.0

3. Results

Figure 2 shows all of the observational data. Each solid line represents a space size distribution over a five-minute period. The envelope of distributions is generally exponential, although there is a variation over a wide range; i.e., the N_O values extend over double figures and the slopes are different. The following procedure was used to determine the characteristics of size distributions from these data.

Principal component analysis is a statistical method for determining the principal portion of a vast data field by a few factors. We therefore used principal component analysis to try to determine the characteristics of snowflake size distributions. Table 1 shows the proportion and accumulated proportion from the first to the twelfth principal components. It should be noted that each proportion of the first and second principal components is more than 10 %. Moreover, the accumulated proportion until the second principal component is over 80 %. Therefore, we can express the major part of the main variation if we adapt the first and second principal components.

The graph on the left of Fig. 3 shows the relationship between the diameter of snowflakes and the eigenvector element of the first principal component, which has the largest variable component. As can be seen in the figure, the values of the eigenvector element range only from 0.2 to 0.35. In order

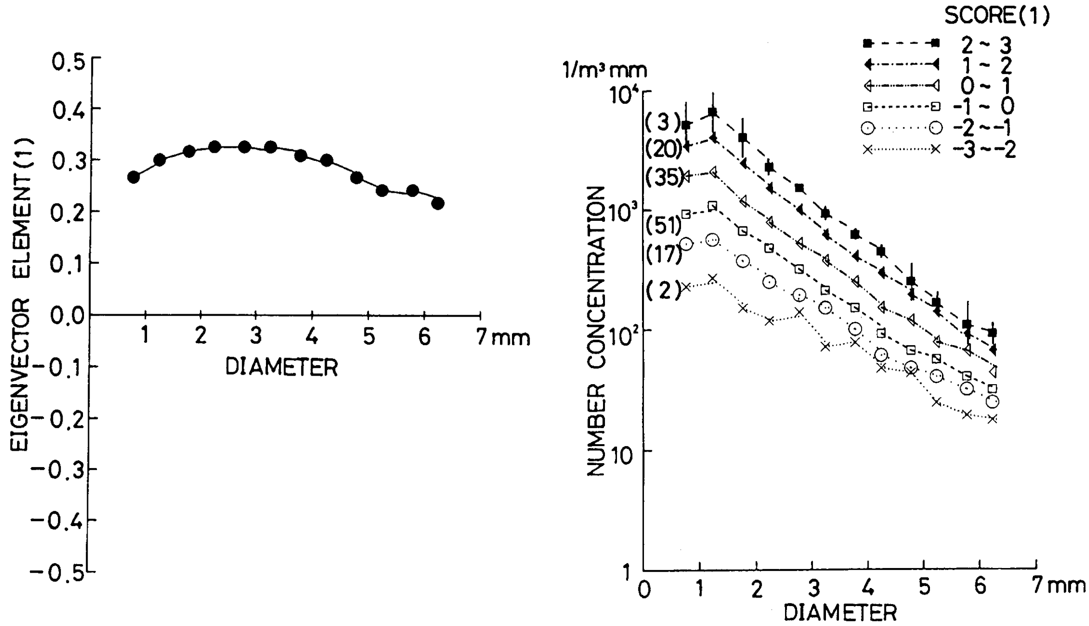

Fig. 3. Relationship between the diameter of snowflakes and the eigenvector element of the first principal component (left), and the size distributions averaged over each score (right), in which vertical lines through each datum point represent the standard deviation and the numerical values in parentheses the data numbers.

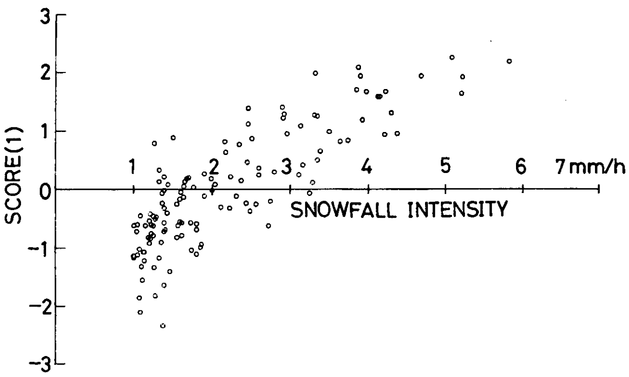

Fig. 4. Relationship between snowfall intensity and score of the first principal component.

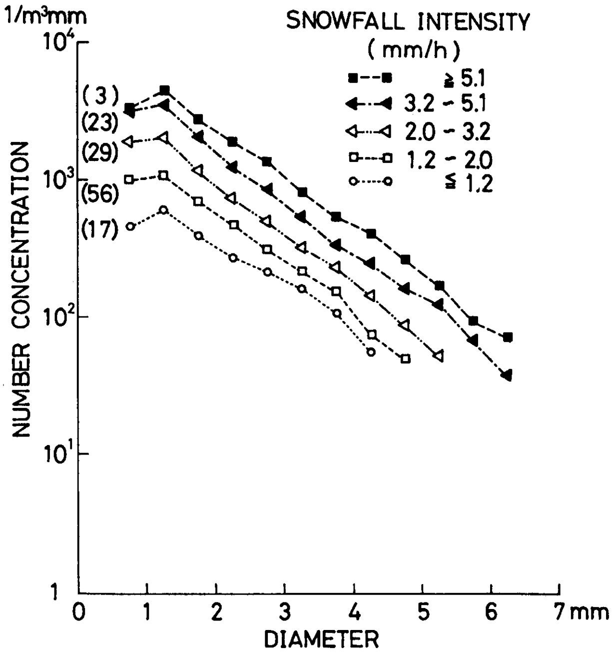

Fig. 5. Size distributions of snowflakes with an equal snowfall intensity. The numerical values in parentheses represent the data numbers.

to clearly show the characteristics, the size distributions averaged over each score are shown on the right of Fig. 3. As can be seen in the figure, each averaged size distribution is an exponential distribution and moves parallel to a higher number concentration with increase in the score value. The smaller number concentration of 0.5–1.0 mm in diameter than that of 1.0–1.5 mm may be due to the sensitivity limit of measurement. Next, we study the meteorological meaning about the score of the first principal component in these statistical results.

Since the number concentrations of snowflakes over all diameters increase as the score becomes higher, the score of the first principle component is thought to be related with the snowfall intensity. Therefore, this relationship is plotted in Fig. 4. As can be seen in the figure, the values of score increase with increase in snowfall intensity. Thus, a "higher score value" is equivalent to a "higher snowfall intensity".

Based on the abovementioned fact, the figure on the right of Fig. 3 is translated to Fig. 5, which

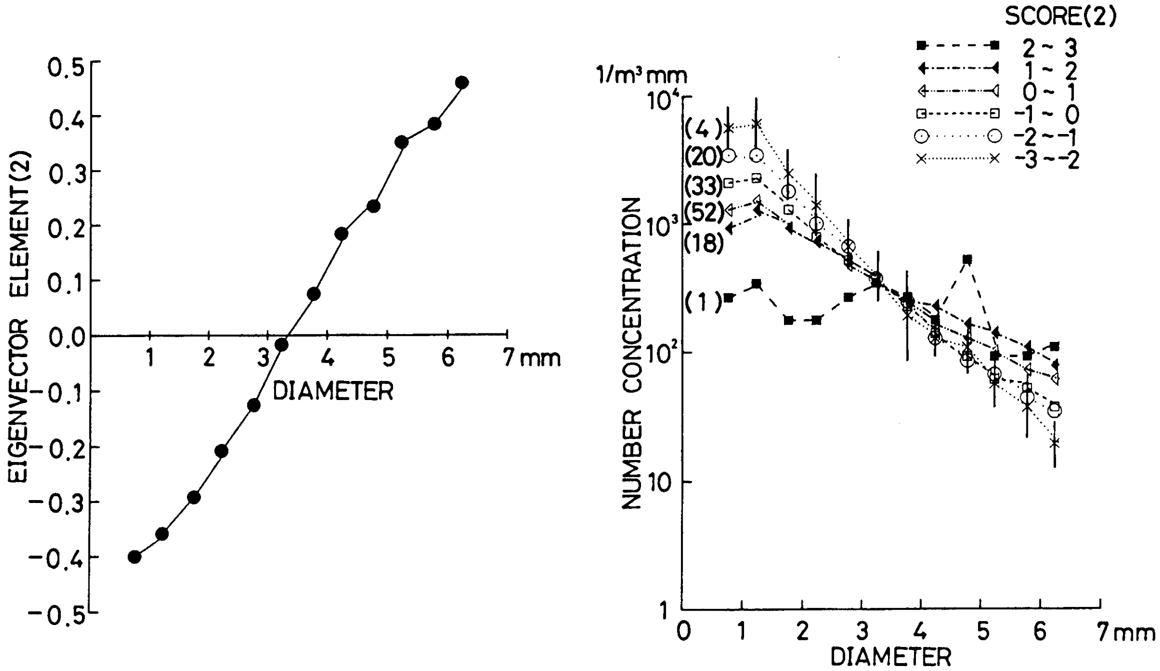

Fig. 6. As in Fig. 3 except for the second principal component.

shows the snowflake size distribution in five steps. The averaged size distribution with an equal snowfall intensity is an exponential distribution, and it moves parallel to a higher number concentration, maintaining the exponential form, with increase in snowfall intensity. These characteristics of size distributions agree with those reported by Gunn and Marshall (1958) with regard to the exponential distribution, but they differ from those of Gunn and Marshall (1958), who reported that both N_O and λ decreased with increase in snowfall intensity.

The graph on the left of Fig. 6 shows the relationship between the diameter and the eigenvector element in the second principal component. In the case of the second principal component, the eigenvector element is seen to increase linearly, changing from minus to plus at about 3 mm. The characteristics are translated to graph on the right of Fig. 6. When the score values increase, the slopes of the size distributions become gentle; that is, the averaged size distributions change from distributions with many number concentrations of small-sized snowflakes and a few number concentrations of large-sized snowflakes, to those decreased in small-sized snowflakes and increased in large-sized snowflakes.

Next, we study the meteorological significance of the score of the second principal component. Figure 7 shows the relationship between the snowfall intensity and the score value of the second principal component. As can been seen in this figure, the score values do not relate to snowfall intensity. In other words, the score of the second principal component is related to physical values other than the

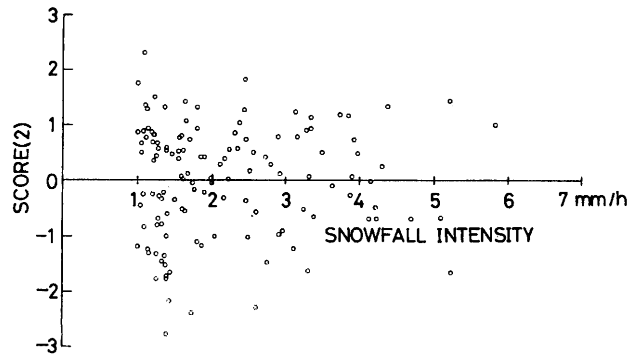

Fig. 7. As in Fig. 4 except for the second principal component.

snowfall intensity.

Next, we study changes in the characteristics of snowflakes with increase in the score values of the second principal component. The size, density, number of snow crystals composing a snowflake, rime amount and so on are considered as the physical values representing the properties of each snowflake. The difference in density of snowflakes is considered to be the cause of the difference in size distributions even under the condition of equal snowfall intensity. Figure 8 shows the relationship between the score of the second principal component and the ratio of averaged falling velocity to the averaged diameter of snowflakes (V/D) of a size distribution. The figure shows that the score values increase when the ratio V/D decreases. The decrease in the ratio V/D is thought to correspond to the change from high density to low density. In other words, the score values increase when the properties of snowflakes change

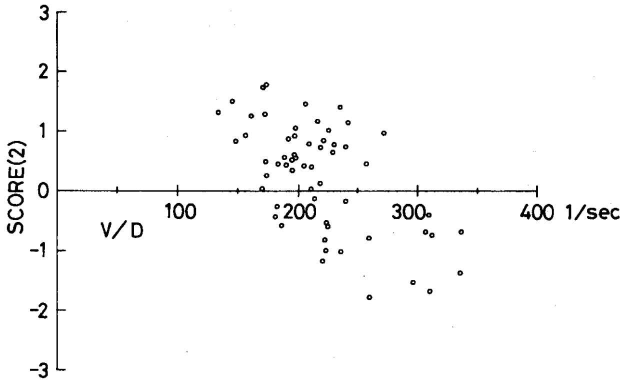

Fig. 8. Relationship between the ratio of averaged falling velocity to the averaged diameter of snowflakes of a size distribution and the score of the second principal component.

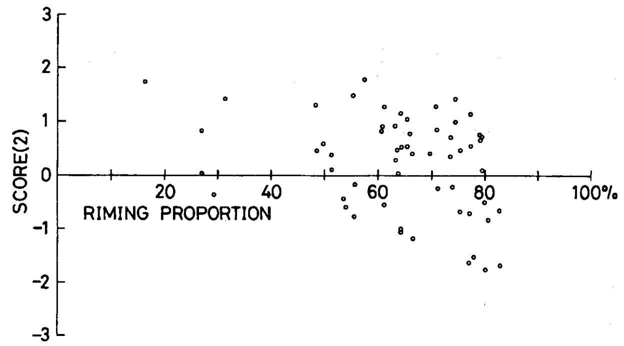

Fig. 9. As in Fig. 8 except for the riming proportion.

from high density to low density. We can therefore say that the slope of the size distribution becomes gentle under this condition. Next, we study the effect of rime amount, which is one of the properties of snowflake. Figure 9 shows the relationship between the riming proportion and the score values of the second principal component, where the riming proportion is defined by the ratio of rime amount to total mass of a snowflake (Harimaya and Sato 1989 and 1992). As can be seen in this figure, the score values increase with decrease in the riming proportion. In other words, the slopes of size distributions become more gentle in the case of snowflakes composed of no rimed snow crystals. Thus, in summary, Figs. 8 and 9 show that the slopes of size distributions become more gentle in the case of snowflakes with a low density, or no rimed snow crystals.

4. Discussion

Figure 10 shows characteristics of snowflake size distributions based on a summary of the observational results. One characteristic is represented by broken lines, which are size distributions shown in Fig. 5. Namely, each averaged size distribution is an exponential distribution and moves parallel to

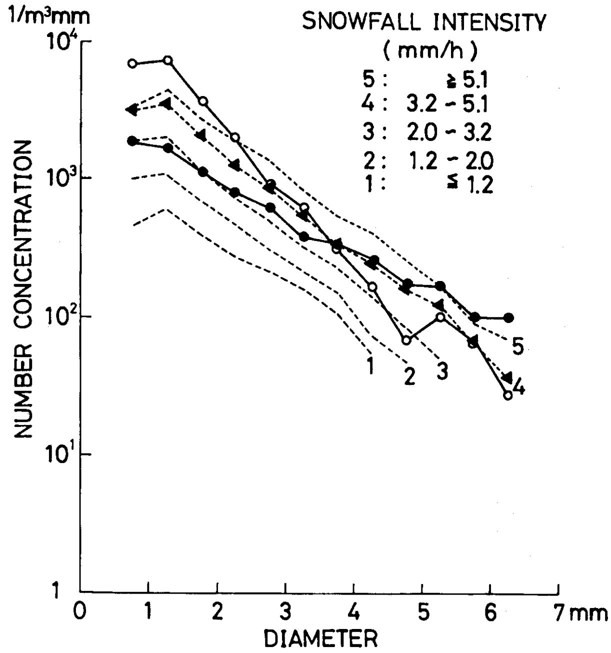

Fig. 10. Distributions with steepest slope (open circles) and with gentlest slope (solid circles) compared with the average distribution (solid triangles) under the condition of snowfall intensity of 3.2–5.1 mm/h.

a higher number concentration with increase in the score values of the first principal component, which has the highest proportion of variations. The other characteristic is represented by solid lines. The size distributions shown by open circle symbols and solid circle symbols correspond to the lowest and highest score values of the second principal component under the condition of 3.2–5.1 mm/h in snowfall intensity, respectively. When the score values of the second principal component increase, the slope becomes gentle even under the condition of equal snowfall intensity; that is, the size distributions change from that shown by open circle symbols, to that shown by solid circle symbols.

The above results have the following meteorological significance. The averaged size distributions with equal snowfall intensity shown by broken lines are exponential distributions and move parallel to a higher number concentration, maintaining their exponential form, with increase in snowfall intensity. Even under the condition of equal snowfall intensity, averaged size distribution with snowfall intensity of 3.2–5.1 mm/h, shown by the solid triangle symbols changes from a steep slope, shown by the open circle symbols, to a gentle slope, shown by the solid circle symbols. The size distributions of snowflakes have the above characteristics.

Even under the condition of equal snowfall intensity, size distributions vary and have a more gentle slope when the ratio V/D decreases, as shown in

Fig. 8. The decrease in the ratio V/D is thought to correspond to the change in properties of snowflakes from high density to low density. The slopes of size distributions become more gentle when the riming proportion decreases, as shown in Fig. 9. In a previous paper (Harimaya and Sato 1992), snowflakes with high riming proportion and high density were reported to be formed in clouds with a high liquid water content that were in the developing or mature stages of growth. Under such conditions, the slope of the size distribution becomes steeper given the increase in the number of small-sized snowfall particles, because cloud droplets are expected to transform into snow crystals. On the other hand, snowflakes with a small riming proportion and low density were formed in clouds in the dissipating stage (Harimaya and Sato 1992). Only a few number concentrations of snow crystals newly originate under such a condition, and therefore there is a remarkable decrease in the number of snow crystals due to the aggregation growth process. As a result, the slope of the size distribution becomes gentle. The growth stage of clouds is thought to affect the size distribution of snowflakes even if the snowfall intensity is equal.

5. Conclusions

In order to reconsider the observational results reported in past paper, we conducted observations of the size distributions of snowflakes on the ground, and we clarified their characteristics and formation mechanisms.

The results of our analysis using a wide range of snowfall intensities and a large quantity of data show that the characteristic of averaged size distributions of snowflakes is that they move parallel to a higher number concentration, maintaining their exponential form, with increase in snowfall intensity. It differs from that of Gunn and Marshall (1958), who reported that both N_O and λ decreased with increase in snowfall intensity. A small variation superposes on the averaged size distribution and changes its slope even under the condition of an equal snowfall intensity. The density and riming proportion of snowflakes are shown to be the factor that determines the slope. In other words, the slope of the size distribution becomes more gentle when snowflakes have low density and are not composed of rimed snow crystals

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形成機構の違いに関連した雪片粒径分布の特徴

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今までの少数データから得られた観測結果を再検討するために、地上で雪片粒径分布の観測を行い、特徴とその形成機構をまとめる。

平均的な粒径分布は、降雪強度が強くなるにつれて指数分布を保ちながら数密度の多い方へ平行移動する。このことは、Gunn and Marshall (1958) の報告した降雪強度の増加とともに粒径分布が広くなるという結果とは異なる。また降雪強度が等しい場合でも、指数分布の傾きを少し変動させるような小さな変化も重なって起こるという特徴があった。その指数分布の傾きを決める要因は、雪片の密度と付着雲粒量であることが示された。