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Snowflake Formation and Its Regional Characteristics

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Abstract

Snowflake formation and its regional characteristics were studied using data obtained from past observations of snowfall phenomena, since snowflake formation contributes substantially to snowfall amount. The collision of component crystals occurred more easily if there was a high concentrations of snow crystals in the atmosphere. Snowflake formation occurred more easily with the progress of growth stages of a snow cloud. The other important parameter was the range of fall speeds. On the other hand, coalescence occurred more easily with temperature rise and with larger component crystals.

There were regional characteristics in which snowflake formation become more active toward inland. The regional characteristics can be explained by the above-mentioned results obtained from observations.

1. Introduction

It is well known that snow particles grow through the processes of deposition, riming and aggregation. Although the deposition process contributes to the growth of snow particles in the early growth stage, both riming and aggregation processes can substantially affect the snowfall amount. The riming process plays an important role in the growth of snow particles in coastal areas of Japan on the Japan Sea side, during northwesterly winter-monsoon season, whereas it is not very important in inland areas (Harimaya and Sato, 1992; Harimaya and Kanemura, 1995). The riming process is an important factor in the formation of orographic snowfall, as snow particles wash out many cloud droplets newly formed when a topographic updraft causes snow cloud to redevelop (Harimaya and Nakai, 1999).

On the aggregation process, the characteristics of snowflake were first studied. Magono and Oguchi (1955) classified snowflakes into small groups, and discussed the crystal types of component crystals and the sizes of snowflakes.

Magono (1953) reported that the size of a snowflake was dependent on the temperature and was largest at -1°C . Later, Hobbs et al. (1974) also reported the same finding. Lo and Passarelli (1982) showed from airborne observations that the collisional breakup process served to limit the number of large snow particles. Higuchi (1960) showed from ground observations that the probability of coalescence between two plane snow crystals was minimum when two crystals are of the same sizes.

The theoretical approach to understanding the aggregation process is as follows. Sasyo (1971) numerically calculated the aggregation of snow particles using a stochastic equation. Later, Sasyo and Matsuo (1980) obtained a conditional probability function of fall speed for a given mass from field observations. Based on the conditional probability function, Sasyo and Matsuo (1985) determined the kernel of a stochastic equation and simulated snowflake aggregations in a cloud with uniform elemental snow crystals without assuming an initial size distribution of snowflakes. Passarelli and Srivastava (1979) determined the collision kernel by assuming a rectangular distribution function for the fall speed and theoretically studied the formation of snowflakes by numerical integration of the stochastic equation. Since these studies were all numerical calculation based on only small amounts of observational data, it is desirable to observe the further statistical property of snowflake.

2. Observational and analytical procedures

Analyses were carried out on data obtained from past observations of snowfall phenomena in order to study the characteristics of snowflakes, the factors influencing snowflake formation, the effect of snowflake formation to snowfall amount, and regional characteristics of snowflake formation. Observations were carried out at Shinoro, Hokkaido during winter in 1992 (Harimaya et al., 1999), Iwamizawa, Hokkaido in 1989 and 1991 (Harimaya and Kanemura, 1995; Harimaya et al., 1999), and Sagurigawa, Niigata Prefecture in 1995 and 1997 (Harimaya and Nakai, 1999; Harimaya et al., 2000) as shown in Fig. 1. Shinoro and Iwamizawa are located at coastal and inland areas of Ishikari Plain, respectively. Sagurigawa is located at an altitude of 400 m on a mountain side of the Mikuni Mountains and is surrounded by mountains over 1,000 m in altitude. As the winter monsoon wind direction is perpendicular to the mountain range, orographic snowfall occurs in Sagurigawa.

Measurements of snowflakes were carried out as follows. Snowflakes were captured on a board covered with a velvet cloth, and one snowflake with a mean

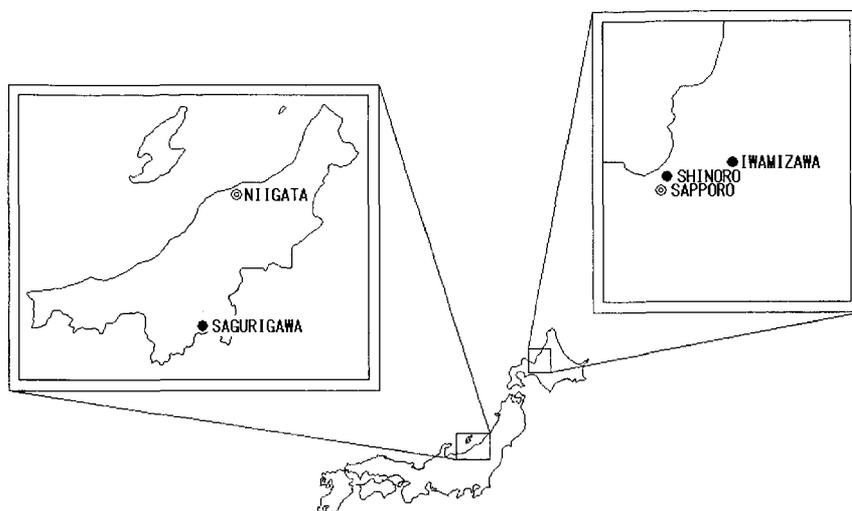


Fig. 1. Location of the observational sites.

degree of riming was selected as a representative snowflake. This snowflake was photographed using a large-sized macro-photographing apparatus. The diameter of the snowflake was measured from the photograph. After that, the snowflake was disassembled into each snow crystal with a bamboo skewer on a glass plate as carefully as possible so that it would not fracture. Then, all of the snow crystals composing the snowflake were photographed. Figure 2 shows an example of a disassembled snowflake. It was used to measure the diameter of each component crystal. The fall speed of a snowflake and its component crystals were calculated using the empirical formulas of Locatelli and Hobbs (1974) and Brown (1970). The riming proportion, which is the ratio of the total riming mass to the total mass constituting one snowflake, was obtained by the method of Harimaya and Sato (1989).

3. Results

3.1 Characteristics of snowflakes

It can be seen from Fig. 2 that a snowflake is composed of many snow crystals. Each snowflake is formed through collision and coalescence of snow crystals. Figure 3 shows an example of the size distribution of component crystals composing a snowflake. In most snowflakes, there are many crystals of small size and a few crystals of large size. The large-sized crystals are

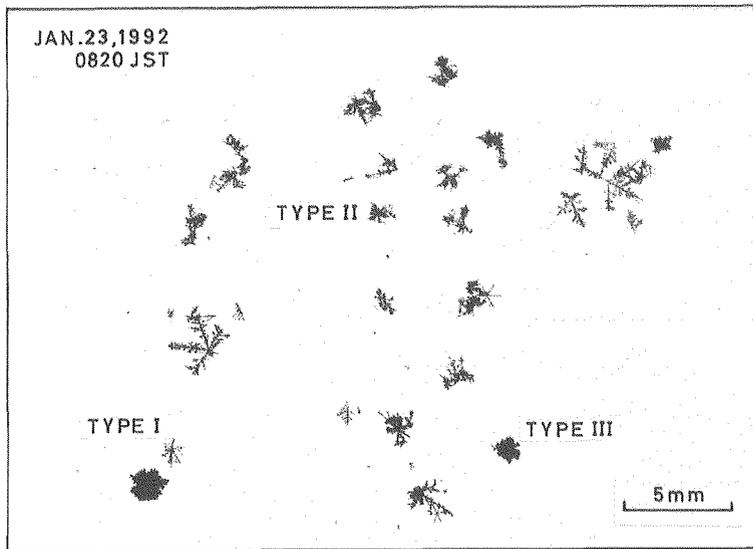


Fig. 2. Photograph of all of snow crystals composing one snowflake.

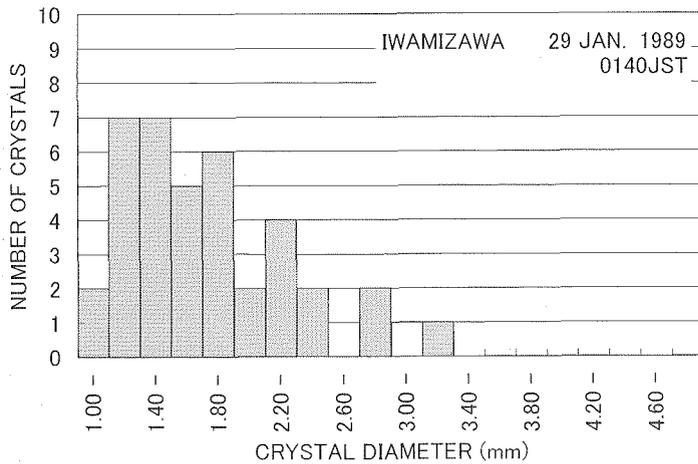


Fig. 3. Size distribution of component crystals composing one snowflake.

thought to grow by collecting small crystals, since there are many small crystals in most snowflakes.

The size of a snowflake has been used as a physical quantity representing the amount of aggregation, as it was difficult to measure the number of component crystals in a snowflake. But, it would be proper that the number of

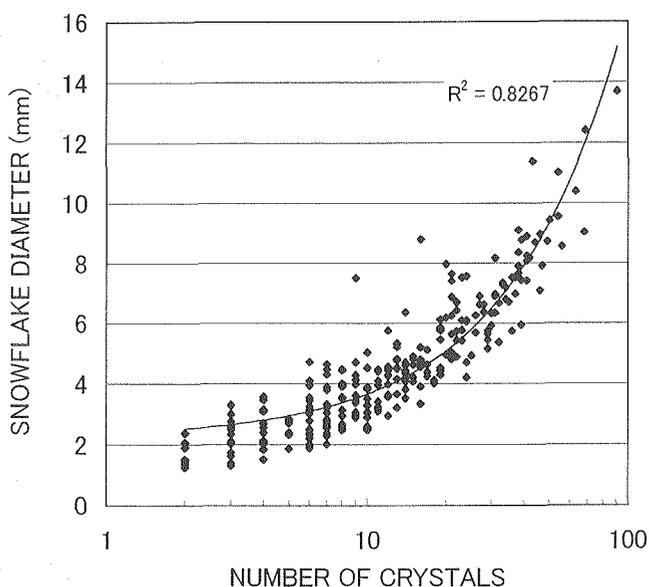


Fig.4. Relationship between number of component crystals and diameter of snowflakes.

component crystals is used as a physical quantity representing the amount of aggregation, since a snowflake grows through an aggregation process. Figure 4 shows the relationship between numbers of component crystals and diameters of snowflakes. It is seen that both parameters can express the amount of aggregation, as the diameter of a snowflake becomes larger with increase in the number of component crystals. However, the number of component crystals would be better as a physical quantity representing the amount of aggregation, as the diameter of a snowflake changes depending on the sizes and compact ratio of component crystals. Therefore, in the following analyses, the number of component crystals was used as a physical quantity representing the amount of aggregation.

3.2 Factors influencing snowflake formation

It is thought that collisions between ice crystals occur more easily and that snowflakes are formed more easily with increase of ice crystals in the atmosphere, since snowflakes are formed through a collision-coalescence process. In order to verify this speculation, the concentration of ice crystals in the atmosphere was calculated at the time when snowflake were falling. The mass of snow particles in unit volume (M : mg/m^3) and the snowfall intensity (R : $\text{mm}/$

hr) were related as $M=250R^{0.9}$ by Gunn and Marshall (1958). On the other hand, the mass of an ice crystal in unit volume (M_{IC} : mg/m³), which is expressed by the difference between the masses of snow and riming amount in unit volume, is expressed by using riming proportion (RP : %) as follows:

$$M_{IC} = M \left(1 - \frac{RP}{100} \right),$$

where M_{IC} is the sum of mass ($\overline{m_{IC}}$: mg) of a component crystal with mean diameter. Then, $\overline{m_{IC}}$ can be obtained from an empirical formula (Harimaya and Sato, 1989) by using the observed mean diameter of unrimed crystals. Therefore, the concentration of ice crystals (N_{IC} : 1/m³) becomes

$$N_{IC} = \frac{M_{IC}}{\overline{m_{IC}}}.$$

Figure 5 shows the relationship between the concentration of ice crystals in the atmosphere and number of component crystals calculated by the above-described procedure. It is seen that snowflakes with many component crystals

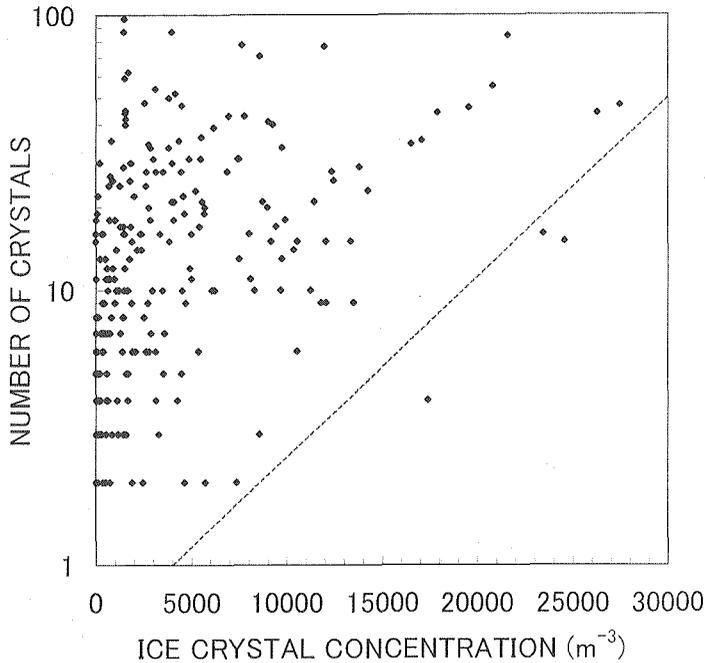


Fig. 5. Relationship between concentration of ice crystals in the atmosphere and the amount of aggregation (number of component crystals).

appear with increase in ice crystal concentrations in the atmosphere. In other words, ice crystal concentration in the atmosphere affects the amount of aggregation.

Based on the above results, further analysis was conducted. Harimaya and Sato (1992) showed from observations that snow particles with large riming proportions fell from snow clouds in developing and mature stages, whereas snow particles with small riming proportions fell from snow clouds in the dissipating stage. These findings indicate that cloud droplets in clouds are depleted with progress of the growth stages of snow clouds. As this is thought to affect the amount of aggregation, the relationship between riming proportion and a physical quantity representing aggregation amount (number of component crystals) was studied, and the results are shown in Fig. 6. Generally speaking, the relationship is seen to be in reverse. Namely, the physical quantity representing aggregation amount is small when the riming proportion is large, whereas the physical proportion is large when the riming proportion is small. Considering this fact together with the results of Harimaya and Sato (1992), it is concluded that the aggregation process becomes more active with the progress of growth stages of snow clouds.

Snowflake formation is thought to be related to the range of fall speed

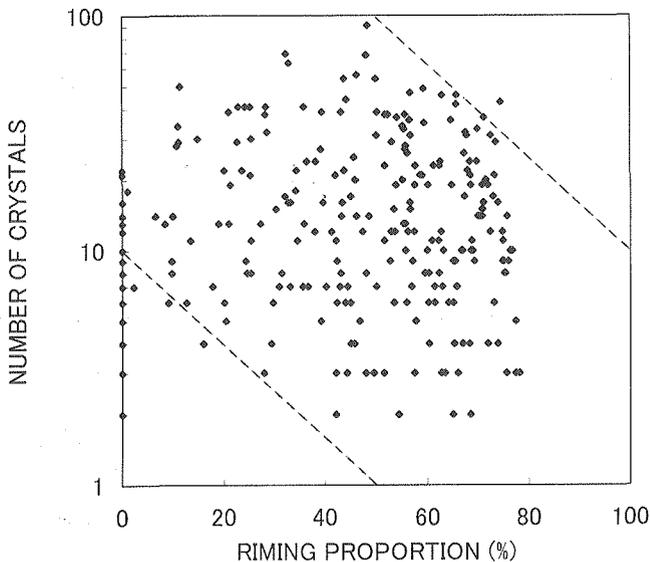


Fig. 6. Relationship between riming proportion and the amount of aggregation (number of component crystals).

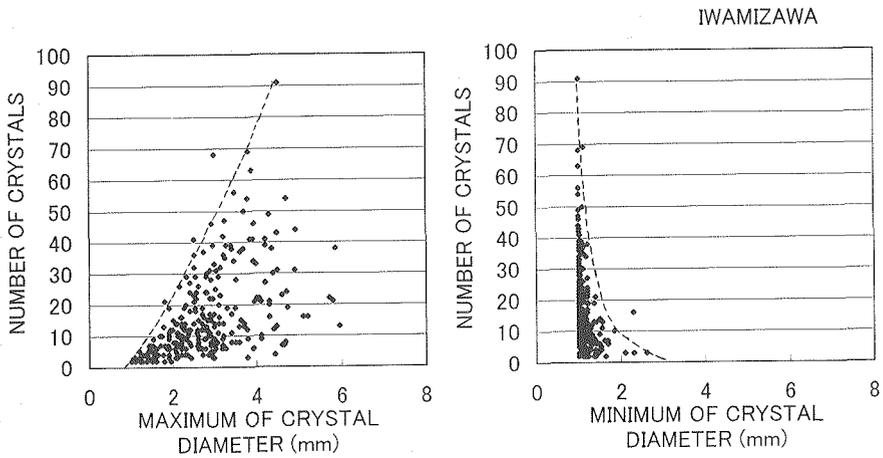


Fig. 7. Relationships between aggregation amount (number of component crystals) and maximum diameter (left) or minimum diameter (right) of component crystals.

distributions in addition to the ice crystal concentrations in the atmosphere. We therefore investigated the relationships between aggregation amount and the size distribution of component crystals related to fall speed. Figure 7 shows the relationships between aggregation amount (number of component crystals) and maximum diameter (left) or minimum diameter (right) of component crystals. It is seen that a snowflake grows in the case of component crystals with a large maximum diameter and small minimum diameter, whereas a snowflake does not grow in the case of component crystals with a small maximum diameter and large minimum diameter. Since it is thought that fall speed affects the amount of aggregation, the characteristics of fall speed were studied. As an example of fall speed distribution, Fig. 8 shows the values calculated from the size distribution in Fig. 3 by empirical formulas. Figure 9 was made on the basis of data shown in Fig. 8. Figure 9 shows the relationship between aggregation amount and range of fall speeds, which is the difference between maximum and minimum values. It is seen that aggregation amount becomes large with increase in the range of fall speeds. It is seen that a rimed crystal, unlike an unrimed crystal, can grow even under the condition of a small range of fall speeds. This suggests that rimed crystals easily coalesce due to the temperature rise by latent heat of riming. This will be discussed later.

Next, the case with which component crystals can coalesce after collision was studied. The ratio of the sum of the component crystal diameters to the diameter of a snowflake expresses the compact ratio of a snowflake. Figure 10

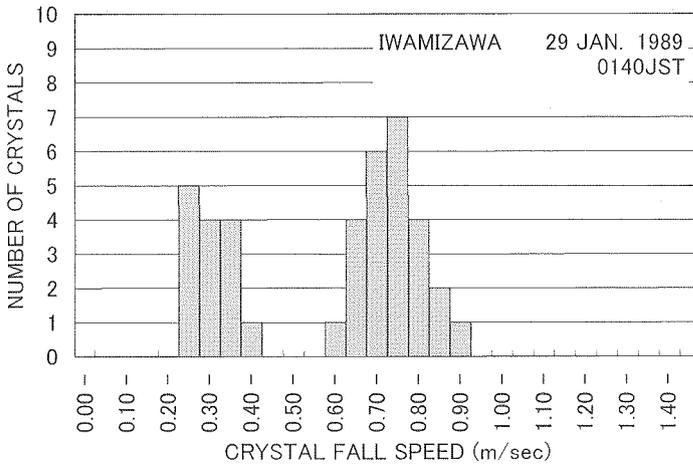


Fig. 8. An example of fall speed distributions of component crystals.

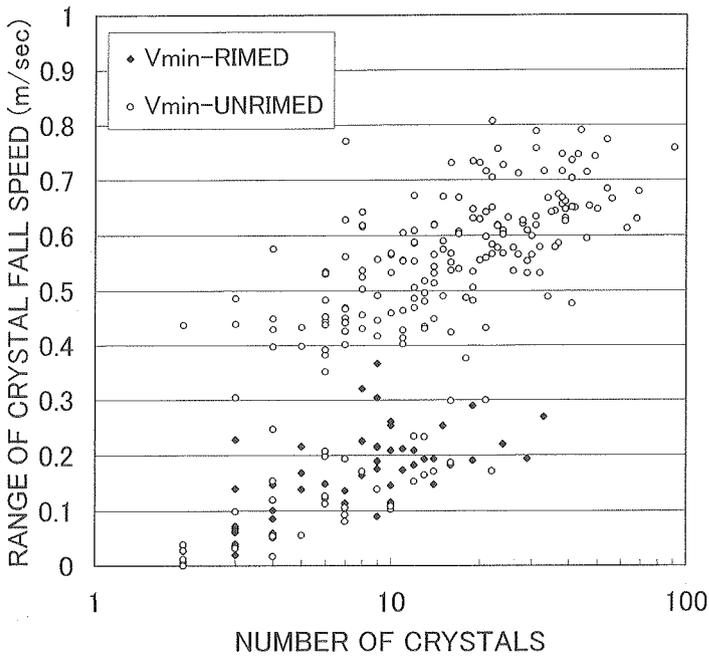


Fig. 9. Relationship between aggregation amount and the range of fall speeds.

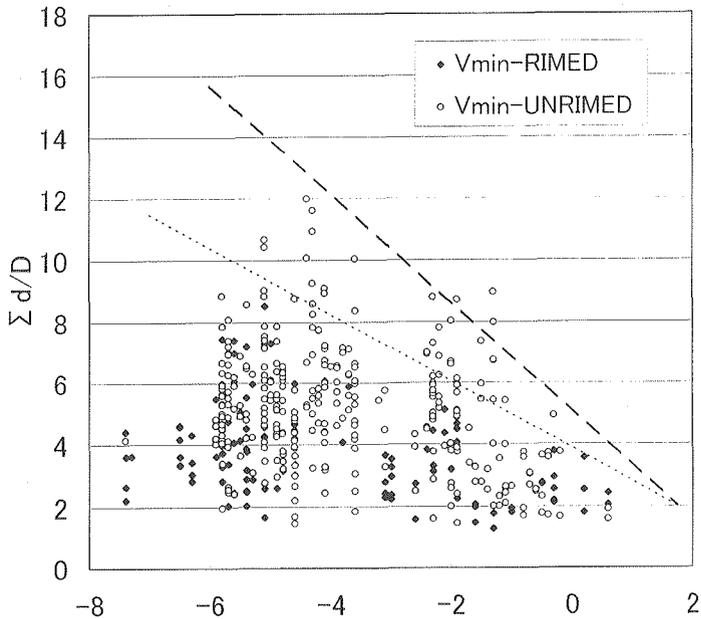


Fig. 10. Relationship between air temperature and compact ratio.

shows the relationship between air temperature at the ground and compact ratio. The dotted line shows the upper limit on rimed crystals, and the broken line shows that on unrimed crystals. It can be seen that both compact ratios become small with rise in air temperature; in other words, the structure of the snowflake becomes coarse. This shows that component crystals can convert into a snowflake by touching at both ends, because the adhesion force increases with rise in air temperature. This result supports the finding of Magono (1953) and Hobbs et al. (1974) showing that snowflake size is dependent on temperature. The rise in temperature due to latent heat of riming may cause the rimed crystals to reach the same level of compact ratio with air temperature colder than that of unrimed crystal. This means that this effect was also favorable for rimed crystals in the range of fall speeds.

3.3 Effect of snowflake formation on snowfall intensity

Figure 11 shows how an increase in snowfall intensity is caused by an increase in the amount of the ice crystals, which is calculated by subtracting the riming amount from total snowfall amount. It is seen that ice crystal intensity increases with an increase in snowfall intensity. Thus, it can be concluded that

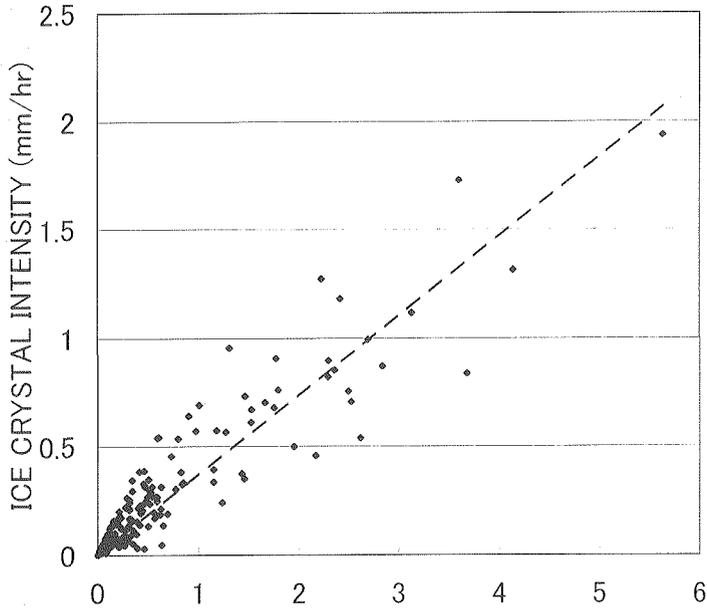


Fig. 11. Relationship between snowfall intensity and ice crystal intensity.

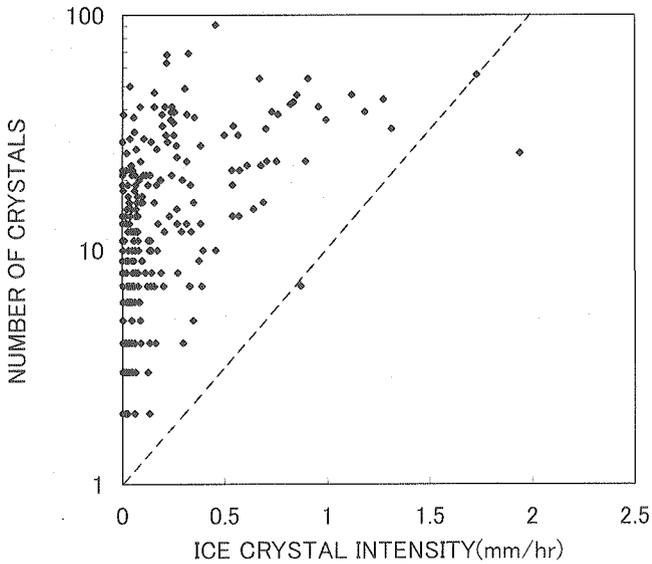


Fig. 12. Relationship between ice crystal intensity and aggregation amount (number of component crystals).

ice crystal intensity affects snowfall intensity. Figure 12 shows the kinds of snow particles that affect ice crystal intensity. It can be seen that a large amount of aggregation causes great ice crystal intensity, whereas a small amount of aggregation causes little ice crystal intensity. Therefore, snowflake formation increases ice crystal intensity.

3.4 Regional characteristics of snowflake formation

Based on the fact that snowflake formation increases ice crystal intensity, the regional characteristics of snowflake formation were studied by using the ice crystal intensity. Figure 13 shows the relationships between snowfall intensity and ice crystal intensity in three regions. The thin solid line, thick solid line, dotted line and broken line show the relationships in Shinoro, Iwamizawa, Sagurigawa under the condition of a strong wind and Sagurigawa under the condition of a weak wind, respectively. In the case of Sagurigawa under the condition of a weak wind, the ratio of aggregation amount to snowfall intensity becomes great in the order of Sagurigawa, Iwamizawa and Shinoro. This shows the order of distance from coast line. In other words, this order shows

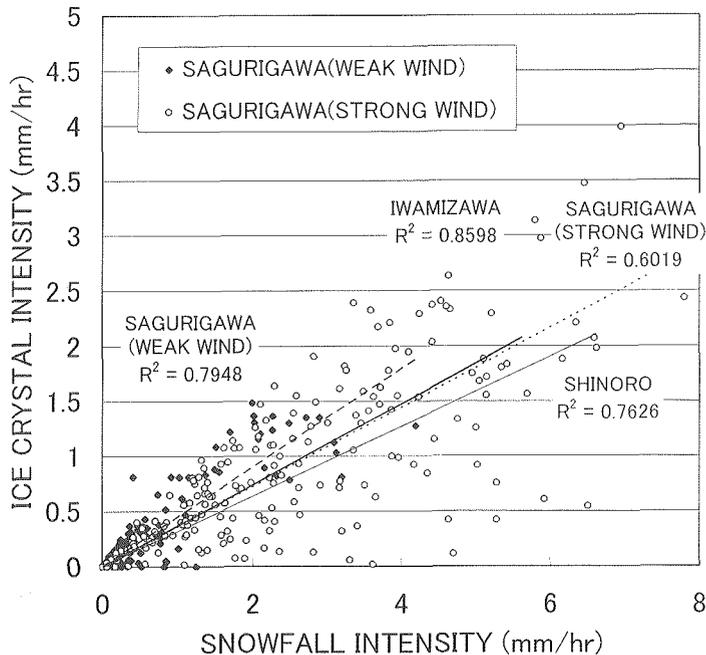


Fig. 13. Relationships between snowfall intensity and ice crystal intensity in three regions.

that snowflake formation becomes more active toward inland.

Next, in the case of Sagurigawa under the condition of a strong wind, the ratio of aggregation amount to snowfall intensity becomes same in Sagurigawa and Iwamizawa. This can be explained by the orographic effect. Because snow particles grow through collection of cloud droplets which are made from topographic updraft at Sagurigawa in a mountain side of the Mikuni Mountains (Harimaya and Nakai, 1999). Therefore, the ratio of aggregation amount to snowfall intensity becomes little compared that under the condition of a weak wind and same in that of Iwamizawa.

4. Discussion

In the previous chapter, the growth stage of snow clouds was pointed out as one cause of regional characteristics in which snowflake formation becomes active toward inland. First, this is considered from the viewpoint of collision of component crystals. Since snowflake formation became more active with a higher concentrations of ice crystals in the atmosphere, this can be explained by the consideration that many ice crystals are born with the lapse of time from the initiation of snow cloud formation.

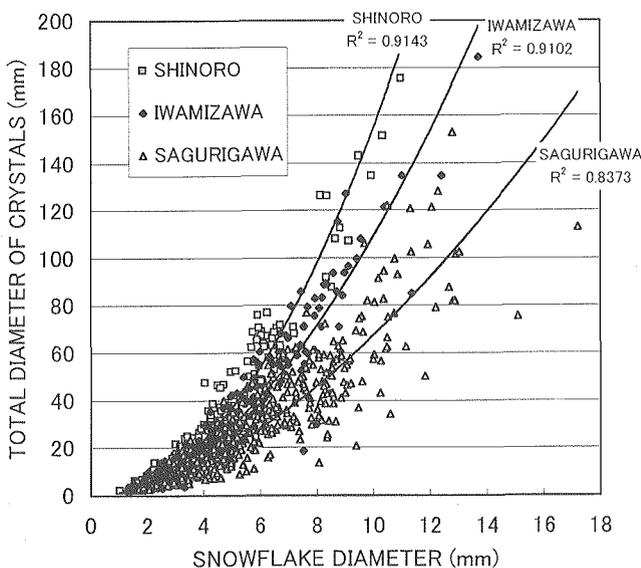


Fig. 14. Relationships between the diameter of a snowflake and total diameter of component crystals in three regions.

Next, regional characteristics of snowflake formation were considered from the viewpoint of coalescence after collision. Here, the compact ratio discussed in section 3.2 was used as the standard of coalescence. Figure 14 shows the relationships between the diameter of a snowflake and total diameters of component crystals. The ratio of total diameters of component crystals to the diameter of a snowflake becomes larger in the order of snowflakes at Shinoro, Iwamizawa, Sagurigawa. Therefore, the compact ratio of a snowflake at Sagurigawa is smallest. In other words, aggregation of ice crystals after collision occurs most easily at Sagurigawa. Coalescence is thought to be dependent on the adhesion strength of ice to ice. Hosler et al. (1957) reported that adhesion strength is dependent on temperature and that it increases with rising temperature. This would explain why coalescence occurs easily at

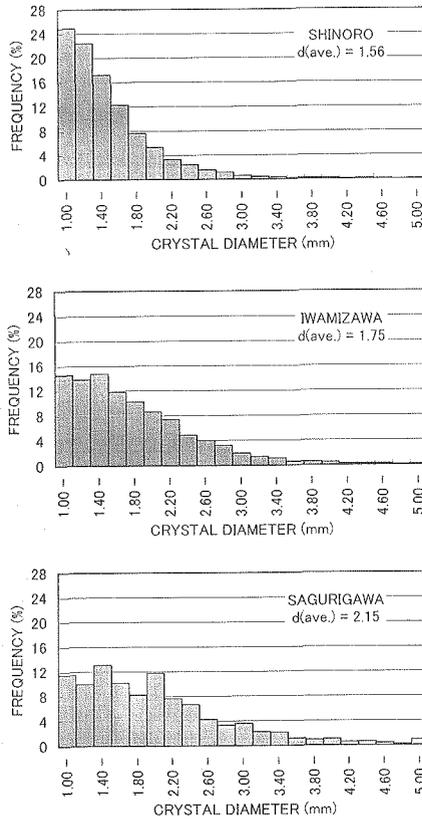


Fig. 15. Comparison with the size distributions of component crystals in three regions.

Sagurigawa, since Sagurigawa has a warmer climate than those at the other two sites in Hokkaido. However, it can not explain why coalescence occurs more easily at Iwamizawa than at Shinoro, since there is no difference between the temperatures at Iwamizawa and Shinoro. If the component crystals are large, it is thought that they become easily intertwined because of the lengths of their branches. Figure 15 shows the size distributions of component crystals at the three sites. The size distribution at Iwamizawa has few frequency in small sizes and some component crystals in larger sizes. The average diameter (1.75 mm) of component crystals in snowflakes collected at Iwamizawa is larger than that (1.56 mm) at Shinoro. This can be explained by the consideration that component crystals grow with the lapse of time from the initiation of snow cloud formation, as Iwamizawa is located far from coast line. The component crystals in snowflakes at Iwamizawa easily intertwine and coalesce, because the component crystals are large. The above results indicates that the regional characteristics of snowflake formation are caused by the lapse of time from the initiation of snow cloud formation regarding collision, and by the temperature difference and the lapse of time from the initiation of snow cloud formation regarding coalescence.

5. Conclusions

The following results were obtained from observations. It was shown from observations that collisions between component crystals occur easily if there is a high concentration of snow crystals in the atmosphere. The relationship between aggregation amount and riming proportion is a reverse one. It follows that snowflake formation occurs more easily with progress of the growth stages of a snow cloud. The other important parameter was shown to be the range of fall speed. Coalescence was shown to occur more easily with temperature rise due to the temperature dependence of the compact ratio and with larger component crystals due to the long lapse of time from the initiation of snow cloud formation.

It was also shown that the ice crystal intensity contributes to some degree to snowfall intensity due to snowflake formation. There were regional characteristics in which snowflake formation become more active toward inland. The regional characteristics can be explained by the above-mentioned results obtained from observations.

Acknowledgments

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