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On Snowflakes of Cold Temperature Types Observed in the Arctic Canada (POLEX-North)

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Abstract

Snowflakes composed of snow crystals of cold temperature types were often observed in mid-winter in the Arctic Canada. The air temperature above the surface was mostly lower than −25℃ during the period (November 1979 to January 1980). Snow clouds and precipitation particles were observed by a vertically pointing radar of 8.6 mm in wavelength. The following is suggested from the discussion of the effects of size, number concentration, falling distance and collection efficiency of snow crystals on the formation of snowflakes.

The non-rimed columns did not form snowflakes owing to its small collection efficiency and the short falling distance. When the level of the radar-echo top was higher than 4 km, the non-rimed combination of bullets grew large and aggregated with each other owing to its large collection efficiency and long falling distance. Cloud droplets might play an important role in the aggregation process in case of snow crystals of cold temperature types, because snowflakes of large size (around 5 mm in diameter) were observed only when snow crystals were heavily rimed in convective clouds.

1. Introduction

Several mechanisms of aggregation of snow crystals have been proposed, such as interlocking, sticking, sintering and pressure melting mechanisms. Until the present, observations of snowflakes composed of various snow crystals have been carried out only at temperatures above −25℃, mostly temperature regions of the growth of dendritic types of snow crystals. The interlocking and sticking mechanisms are thought to be responsible for the fomation of dendrite aggregates. On the other hand, at temperatures below −25℃ there are no observations of snowflakes and no reports on adhesion mechanisms of natural snow crystals.* It is not clear therefore that whether those mechanisms for snowflake formation valid at temperatures above −25℃ are able to be extended to the phenomenon occurring at temperatures below −25℃, or not.

Fortunately we had a chance to participate POLEX-North project at Inuvik (68°22′N, 133°42′W) in the Arctic Canada in mid-winter (Nov. 1979 to Jan. 1980). During our observation period surface air temperature changed from −9 to −43℃ and mostly (about 90%) was lower than −25℃. And we often observed snowflakes on the ground. The purpose of this paper is not to discuss the adhesion mechanisms of snow crystals, but to elucidate conditions under which snowflakes were formed at air temperatures below −25℃ in the Arctic Canada in mid-winter.

2. Data

Snow clouds and precipitation particles were observed by using a vertically pointing radar of 8.6 mm in wavelength. Precipitation particles were simultaneously observed on the snow surface and were directly replicated on glass slides (25×75 mm) coated with 0.5% Formvar solution at 5 or 10 minutes intervals. The glass slides were mostly exposed for more than 30 seconds to replicate precipitation particles, since the precipitation intensity was very weak.

Each case of observation is composed of whole data obtained from 00 to 12 LST or from 12 to 24 LST. As routine radiosonde observations were carried out only twice daily (05 and 17 LST) at the Inuvik Upper Air Station, at the first approximation we assumed that the vertical profiles of air temperature observed at 05 and 17 LST represent their profiles from 00 to 12 LST and from 12 to 24 LST, respectively.

As mentioned above, precipitation particles were directly replicated on glass slides coated with 0.5% Formvar solution. It should be noted that the procedure may lead to provide errorneous results, since snowflakes are easily broken up when they are captured on a glass slide and snow particles may aggregate on the surface of a glass slide when it is coated with Formvar solution too thick. It is therefore difficult to assess whether snow particles obtained on a glass slides are originally snowflakes or not only from their replicas.

* P.G. Stickel (Aeromet. Inc. Tulsa, OK, U.S.A.) observed ice aggregates at temperatures near −50℃ in cirrus clouds (private communication).

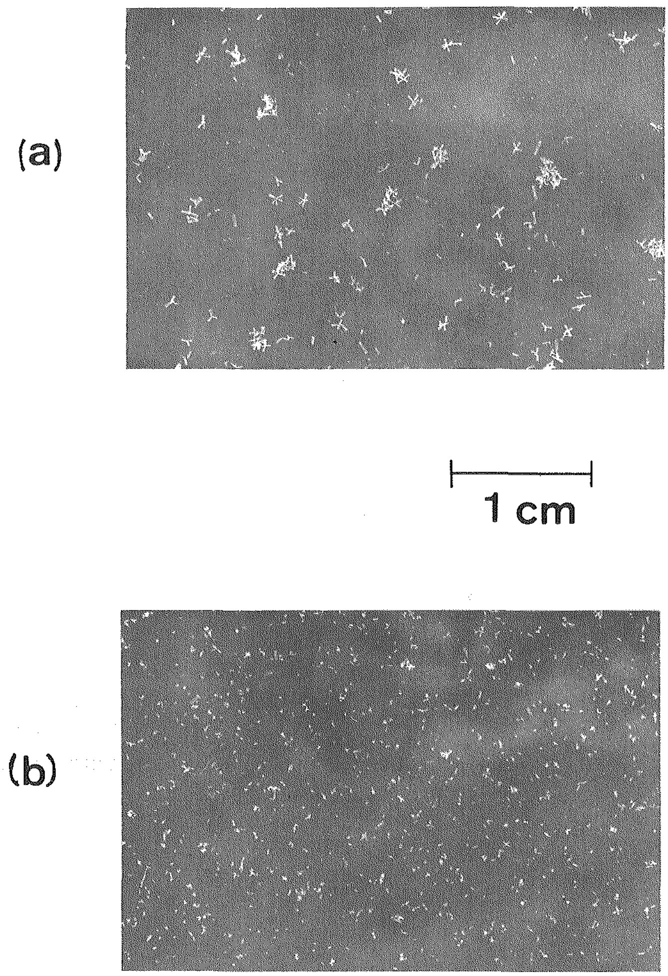

Photo. 1 Typical examples of (a) "snowflake" observed 4 Jan. 1980 and (b) "no-snowflake" observed 11 Dec. 1979.

However, as we made microphotographic observations simultaneously, it is possible to understand whether falling snow particles are snowflakes or single crystals. Photo. 1 shows typical examples of (a) "snowflake" and (b) "no-snowflake".

3. Results

Figure 1 shows the air temperature condition when snowflakes were ob-

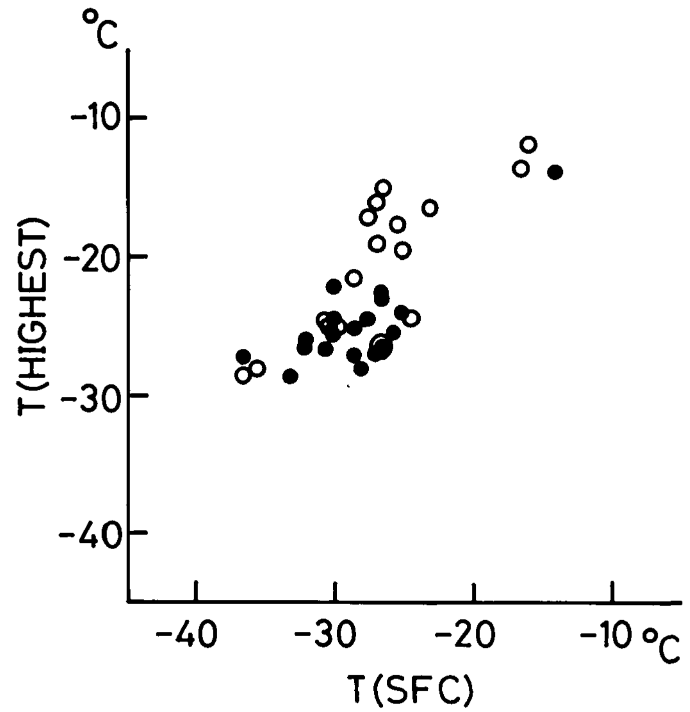

Fig. 1 Temperature dependence of the formation of snowflake. The abscissa and the ordinate respectively represent surface air temperature (T(SFC)) and the highest air temperature (T (HIGHEST)) in the layer through which snow particles fell. Open and solid circles correspond to "snowflake" and "no-snowflake", respectively.

served on the ground. The abscissa and the ordinate respectively represent the surface air temperature and the highest air temperature in the layer from the level of the radar-echo top to the ground surface. The latter temperature would be almost the same with the highest air temperature in the layer through which snow particles fell. Open and solid circles correspond to "snowflake" and "no-snowflake", respectively. In most cases in Fig. 1 the level where the highest air temperature appeared was high above and not near the ground surface, since an intensive inversion of air temperature frequently appeared in the Arctic Canada (Takeda et al., 1982). Snowflakes were observed with a high frequency when the highest air temperature was above −20℃, and were observed with a rather low frequency when it was below −20℃. However, it should be noted that there appeared "no-snowflake" even when the highest air temperature was higher than −14℃, and that there appeared "snowflake" even

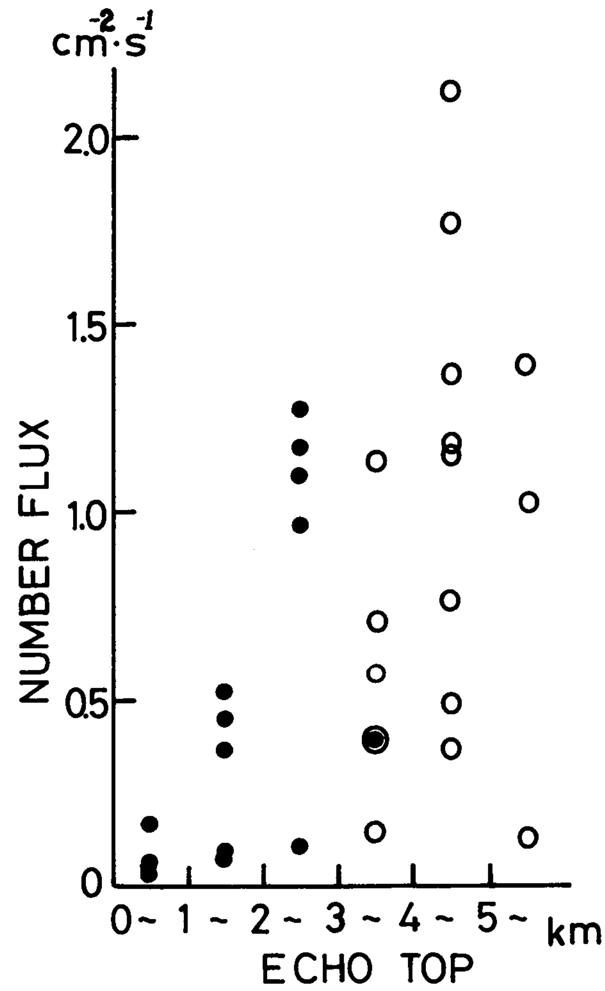

Fig. 2 Effects of number flux and falling distance of snow particles on the formation of snowflake. The abscissa and the ordinate represent the radar-echo top (km) and the maximum number flux ($cm^{-2} \cdot sec^{-1}$) of snow particles observed in each case, respectively. The height interval of the level of the radar-echo top is taken as 1 km.

when the highest air temperatures were below −28℃. Therefore, besides the air temperature, other factors are suggested to affect the rate of formation of snowflakes.

Figure 2 was made to see the effect of number flux of snow particles and their falling distance on the rate of formation of snowflakes. The abscissa and

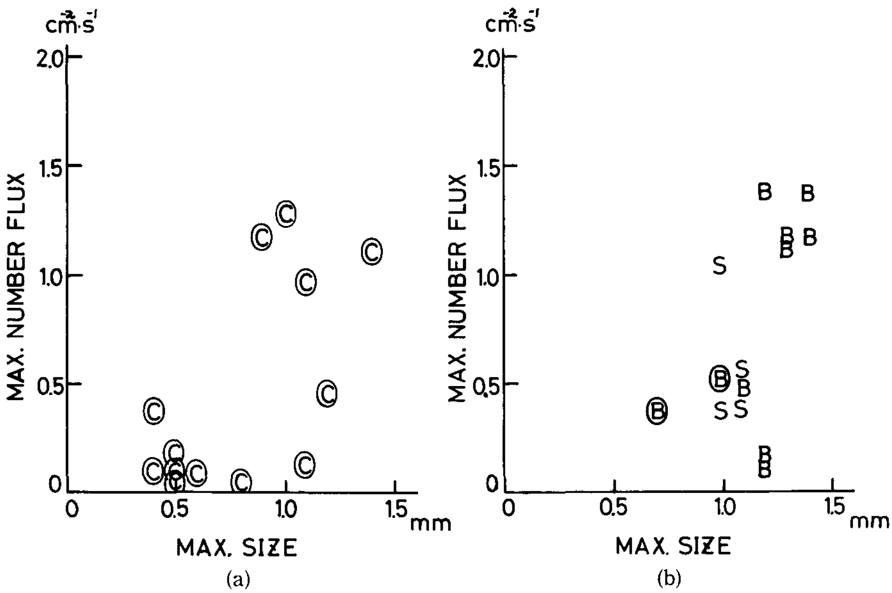

Fig. 3 Effect of the type of non-rimed snow crystals on the formation of snowflakes. The abscissa and the ordinate respectively represent the maximum number flux of snow crystals obtained in each case. B, C, and S mean that the bullet, column, and crossed-plates fell predominantly in the case. Encircled symbols represent "no-snowflake".

the ordinate represent the radar-echo top (km) and the maximum number flux ($cm^{-2} \cdot sec^{-1}$) of snow particles observed in each case, respectively. The height interval among the levels of the radar-echo top is taken to be 1 km. It is seen from Fig. 2 that snowflakes were observed regardless of the maximum number flux. However, we could not say conclusively about the effect of the number flux on the rate of formation of snowflakes, because the number fluxes measured on the ground did not correspond to those in the layer where snowflakes were formed. Figure 2 also shows that snowflakes were observed in almost all cases where the levels of the radar-echo top were above 3 km, whereas they were not observed in all cases with the levels below 3 km.

Figure 3 shows the effect of type, that is shape, of non-rimed snow crystals on the rate of formation of snowflakes. When many types of snow crystals fell simultaneously, the "type" denotes that of snow crystals which fell predominantly over other types. The abscissa and the ordinate respectively represent the maximum size of individual snow crystals on the glass slides and the maximum flux of snow crystals observed in each case. As shown in Fig. 3 (a), snowflakes were not observed when non-rimed columns with any size and number flux fell predominantly. On the other hand, snowflakes were observed when the crossed-plates and the combination of bullets fell predominantly. Especially, snowflakes composed of combination of bullets were often observed. The maximum size of the individual non-rimed combination of bullets tends to be larger in "snowflake" than that in "no-snowflake".

The results shown above lead to the following findings: Snowflakes were not observed when the radar-echo top was below the level of 3 km, but observed when the radar-echo top was above the level of 3 km. The types of non-rimed crystals which composed snowflakes were the crossed-plates and the combination of bullets, and no snowflakes composed of the column was observed. In our previous paper (Fujiyoshi et al., 1982) we found that the type of snow crystals observed on the ground was closely related to both the level of the radar-echo top and the radar-echo intensity near the ground. Also we pointed out that the height of cloud layers, the type of clouds and the type of snow crystals observed on the ground differed according to meteorological situations in mid-winter in the Arctic Canada (Kikuchi et al., 1982; Takeda et al., 1982). Therefore, we will discuss in the following under what meteorological situations snowflakes were observed.

Table 1 gives the level of the radar-echo top and all cases of our observation classified according to meteorological situations defined by Takeda et al., (1982). N.F., F. and F.L. represent "no-snowflake", "snowflake" and "large snowflake", respectively. "Snowflakes" are defined to have maximum diameter

Table 1 Classification of all cases according to meteorological situations and the level of the radar-echo top. N.F., F. and F.L. represent "no-snowflake", "snowflake" (small or moderate size), and "large snowflake", respectively.

Period / Echo Top	A			B			C		
	N.F.	F	F.L.	N.F.	F	F.L.	N.F.	F	F.L.
0 ~ 1 km							9		
1 ~ 2				1			5		
2 ~ 3				3			1		
3 ~ 4		3	1	1				1	
4 ~ 5		2	3					3	
5 ~		3						1	

less than 5 mm and the snow crystals composed a "snowflake" are sparsely packed. "Large snowflakes" are defined to have maximum diameter above or around 5 mm and the snow crystals composed a "large snowflake" are densely packed. Snowflakes were always observed when warm air intruded into the Arctic Canada from the Pacific Ocean at middle levels (period A). They were not observed when a cold air-mass originating from the Arctic Ocean spread over the observation site (period B). When a thick isothermal layer was formed due to the cooling of air-mass caused by the heat exchange with very cold ground surface (period C), snowflakes were observed only when the level of the radar-echoes with the high radar-echo top (above 3 km) appeared, snowflakes (F.) fell during both periods A and C. Large snowflakes (F.L.) fell only when the convective type of radar-echoes appeared and when they were composed of the heavily rimed column, combination of bullets, crossed-plates or their combinations.

4. Discussion and summary

Snowflakes composed of snow crystals of cold temperature types were observed only when the level of the radar-echo top was higher than 3 km. When a layer type of radar-echo appeared, snowflakes with a small or moderate size composed of non-rimed combination of bullets or non-rimed crossed-plates were observed. Snowflakes composed of non-rimed columns were not observed. Large snowflakes were composed of heavily rimed snow crystals. For combination of bullets, their size was larger when snowflakes were observed than that when they were not observed. Size of the crossed-plates composed of snowflakes was smaller than that of the combination of bullets composed of snowflakes.

In the following we will elucidate the effects of size, number concentration, falling distance and collection efficiency of snow crystals on the formation of snowflakes. Jiusto (1971) found the following equations for a different type of snow crystal from cold types discussed in this paper. However, we will use the equations because there is little data on snowflakes composed of cold types of snow crystals, and our purpose of calculation is only to estimate roughly the effects stated above. Equations for the growth of snowflakes are as follows;

$$\frac{dn}{dt} = r_f^2 E N_c (V_f - V_c)$$
$$V_f = 150 r_f^{0.2}$$
$$r_f = 0.25 n^{\frac{1}{2}} r_c,$$

where n is the number of crystals per snowflakes, E the collection efficiency, r_f the radius of the snowflake, N_c the concentration of individual snow crystals in the cloud, and V_f and V_c the fall velocity of flakes and crystals, respectively. It is assumed that a three-crystal snowflake initially exists, and that $V_c = 50$ cm • sec^{-1}. The equation set is solved numerically for the cloud crystal concentration (N_c) and fixed crystal sizes (r_c).

Figure 4 shows the results of calculation. The ordinate and the abscissa represent the number of crystals per snowflake and falling distance, respectively. As shown in Fig. 3 (b), the combination of bullets formed snowflakes when its diameter was larger than 1.0 mm, and did not form snowflakes when it

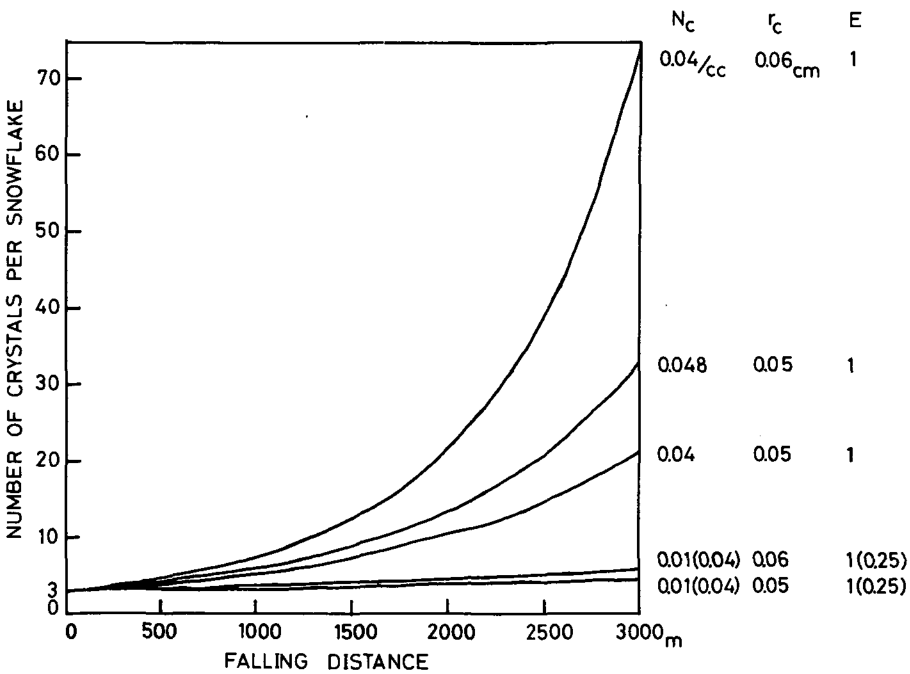

Fig. 4 Results of calculation using the same equations found by Jiusto (1971). The ordinate and the abscissa represent the number of crystals per snowflake and falling distance, respectively. N_c, r_c and E represent the concentration of individual ice crystals in the cloud, the cloud crystal size and the collection efficiency. respectively.

was smaller than 1.0 mm. As seen in Fig. 3, the number concentrations of snow crystals are smaller than 0.04 cm^{-3}if we assume that $V_c=50$ cm • sec^{-1}. The results of calculation for $(N_c, r_c)=(0.04, 0.5)$ and (0.04, 0.6) show that there appears a large difference in number of crystals between them with increasing falling distance in spite of the small difference in r_c. As clearly seen from the equation set and the results of calculation for $(N_c, r_c)=(0.048, 0.5)$, (0.04, 0.5) and (0.04, 0.6), an increase in size of snow crystals leads to a larger increase in number of crystals per snowflake rather than that in the concentration of individual snow crystals. On the other hand, when the concentration of snow crystals is as low as 0.01 cm^{-3} or the collection efficiency is as low as 0.25, the aggregation is quite slight. These results may correspond to the fact that column type of ice crystals did not readily aggregate, since the collection efficiency of the column would be smaller than that of both the combination of bullets and the crossed-plates as expected from their shapes.

During our observation period from Nov. 1979 to Jan. 1980 at Inuvik in the Arctic Canada the column type of snow crystals fell predominantly from low level and thin clouds (Fujiyoshi et al., 1982 ; Kikuchi et al., 1982 ; Takeda et al., 1982). The collection efficiency of the column would be smaller than those of both the combination of bullets and the crossed-plates as expected from their shapes. Therefore, the reason why snowflakes composed of non-rimed columns were not observed may be ascribed to the short falling distance and the small collection efficiency of the column.

The combination of bullets with large size fell predominantly, when the layer type of the radar-echo appeared and the level of the radar-echo top was higher than 4km (Fujiyoshi et al., 1982). The crossed-plates fell predominantly when the level of the radar-echo top was above 3 km. Therefore, when the non-rimed combination of bullets or the non-rimed crossed-plates fall predominantly, these crystals would have a greater chance of aggregation during their fall because of the larger collection efficiency than that of the columns and long falling distance.

Large snowflakes were observed only when the convective type of the radar-echo appeared. The collision frequency among snow crystals would be large in the turbulent atmosphere. Increase in collision frequency would also result in increase in not only aggregation but also disintegration of snow particles because the effects of the ice adhesion mechanism such as the sticking would be small when air temperature is low. Therefore, large snowflakes would not be formed solely by the result of the increase in collision frequency. It should be pointed out that non-rimed snow crystals did not form large snowflakes, but heavily rimed snow crystals did. If the collision frequency of cloud droplets with the snow crystals is high, the contact point(s) between crystals would be cemented before they separate. Therefore, the freezing of collected cloud droplets by snow crystals is suggested to play an important role in aggregation process when air temperature is low.

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