Observation of Snow Crystals in the Lower Atmosphere of Arctic Canada by Means of “Snow Crystal Sondes”

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Abstract

Observations of snow crystals in the lower atmosphere of Arctic Canada were made by means of snow crystal sondes. The number and shapes of crystals, the size distribution of hexagonal plates and columnar crystals at each observation height and the growth mode of columns were studied in the air temperature of $-21$ to $-31^\circ C$.

The results show that snow crystals of peculiar shapes were involved constantly amounting to about 2.5% of total number in the height from surface to 150 m. Although the predominant shapes of snow crystals were columns, single bullets, crossed plates and combination of bullets, hexagonal plates were also observed in considerable percentage.

The growth mode of columns was similar to that of columnar crystals observed by Sato et al. (1981) at South Pole Station. The mean sizes of hexagonal plates and columnar crystals were gradually increased with the decrease of observation height. This may be due to the existence of enough amount of water vapor for growth of those crystals in the atmosphere near surface to several hundred meters in height, locally around the observation site.

The mass growth rate of columns was $2.5 \times 10^{-9}$ g sec$^{-1}$ at the air temperature of $-31^\circ C$, and was larger than that obtained in field observation at $-35^\circ C$ by Kikuchi and Hogan (1979) and that obtained in cold chamber experiment at $-26^\circ C$ by Yamashita (1974). It seems that this discrepancy of mass growth rate at cold temperature regions is caused by the difference of size or mass of crystals.

1. Introduction

The so-called “Snow Crystal Sondes” were designed by Magono and Tazawa (1966), and it has been shown that this sonde is quite useful in the observations of vertical structures of snow clouds (Tazawa and Magono, 1973; Magono and Lee, 1973). For example, utilizing this sonde direct observations of the vertical distribution, mass growth rate and number concentration of snow crystals could be carried out in snow clouds, together with recording of peculiar shapes of snow crystals (Kikuchi, 1974).

It is well known that the growth of snow crystals from vapor phase is an important part of precipitation process. The field or laboratory experiments on the mass growth rate of the crystals have been made by many researchers (see, Fig. 15). However, there are few observations under the freely falling condition of crystals in cold regions (temperature below $-20^\circ C$). On the other hand, the numerical computation of diffusion equation for snow crystal growth in a super-cooled cloud was performed over the wide range of temperature by several authors, for example Koenig (1971), Jayaweera (1971) and Miller and Young (1979). In particular, the scheme for simulating snow crystal growth by Miller and Young (1979) shows the reasonable agreement of crystal mass as a function of time with the
In this article, the results of observations of snow crystals in the lower atmosphere in cold regions by means of snow crystal sondes are described and the estimated mass growth rate of columns is compared with the data of previous other experiments. The observation was conducted for three days at O niak Channel in the outskirts of Inuvik (68°22'N, 133°42'W), N.W.T., Canada (Fig. 1), during our 1977 Arctic expedition (Magono, 1978). In the present analysis, typical examples (SC-4 and SC-5) of data observed on 1 February are used.

2. Synoptic condition on 1 February, 1977

Fig. 2 shows weather maps at surface, 850 mb and 700 mb at the time near the observation time (1150 to 1432 LMT) of snow crystals. As seen in those weather maps, a low pressure system accompanying with fronts situated near the coast of Araska Peninsula and warm air spread over Canada, particularly at middle levels. The vertical structure of atmosphere on 1 February observed at Inuvik Upper Air Station (see, Fig. 1) is shown in Fig. 3. In this figure, the vertical distribution of humidity with respect to water ($H_w$) and to ice surfaces ($H_i$), temperature and wind are shown from the left to right. It is seen that the wind in layers below about the 800 mb level were considerably light and extremely different from those above this level, and a very intensive inversion layer was formed in the levels below about 700 mb.

Those facts suggest that there was a frontal surface at about 750 mb level and a warm air mass over Inuvik at middle levels. This temperature profile is considered to be similar to the period A called by Takeda et al. (1981). It is reasonable to say that this profile have been formed as a result of the advection of warm air mass originated from the Pacific Ocean at middle levels and the outbreak of cold air mass originated from the Arctic Ocean, as seen in Fig. 2.

It can be seen in Fig. 3 that two cloud layers have been formed at 0500 LMT. On the other hand, the upper cloud layer disappeared at 1700 LMT and the lower cloud layer, whose temperature of lower part was nearly constant with
height, became thicker. This type of vertical profile of temperature in cloud layer is similar to the type II termed by Takeda et al. (1981).

In the afternoon on 1 February, Ac and/or Sc type of clouds were observed and the amount of snow fall was 1.6 cm at the observation site of Inuvik.

3. Method of observation and analysis

In this observation, the snow crystal sondes were suspended from a tethered balloon and were raised to 150 or 200 m in effective height on the leeward. During the ascent, the tethered balloon was held at regular intervals of height at 1.5 or 2 minutes, and during this time the snow crystals were trapped by the sondes.

The sampling and recording mechanism of the snow crystal sonde is explained in the original paper of Magono and Tazawa (1966) in detail. Falling snow crystals entered at the inlet of the sonde and were fixed by a replica solution on the 35 mm film surface, as seen in Fig. 4. Using a microscope, the film is scanned over all surfaces successively and all crystals are photographed. Utilizing the negative films developed, the number and dimension of the crystals are examined by means of magnifying glass. The total magnification of this process was 150.

The observed snow crystals were classified into several types according to their shapes, namely peculiar or unsymmetrical shapes (Kikuchi, 1969,
1970), solid and hollow columns, single bullets, combination of bullets, crossed plates, hexagonal plates and unidentified particles. The percentages of those types of crystals to the total number were calculated for each trapping height and also the flux of snow particles was estimated from the total number of crystals, the holding time at each height and the opening area of inlet (3×4 cm). Moreover, the peculiar shapes of crystals were classified into the nine groups by the growth mode or correlation (Kikuchi, 1974). The nine groups (A to I) of peculiar crystals are described in the previous paper (Kajikawa et al., 1980), in detail.

4. Results

4.1 The percentage frequencies of several types of snow crystals at each observation height

Figs. 5 and 6 show the frequency of seven types of snow crystals including the peculiar or unsymmetrical shapes at each observation or trapping height. In those figures, only the surface data were obtained using ordinary replicated glass slides. \( N \) and \( F \) mean the total number and flux of snow crystals, respectively. The scatter on flux data was responsible for the difference of trapping behavior of the snow crystal sonde at each observation height. In general, the flux at lower heights are of small value except for that of the surface.

The seven types of crystals and the representative peculiar crystals were illustrated schematically, according to the manner of Magono and Lee (1966) and Kikuchi (1974). In those observations, because the replicating condition of the snow crystal sondes was not complete, unidentified types of crystals amounted to about 30%. However, those types may be a combination of bullets and crossed plates, when a comparison was run against the results of surface observations (see, Fig. 5).

Although the main shapes of snow crystals in those cases were columns, single bullets, combination of bullets and crossed plates being analogous to the case of Fujiyoshi et al. (1981), hexagonal thin plates were also observed in a
Fig. 5 Percentage of the seven different shapes of snow crystals observed at 1150 to 1203 LMT on 1 February 1977. N and F mean the total number and flux of crystals, respectively.

Fig. 6 Percentage of the seven different shapes of snow crystals observed at 1415 to 1432 LMT on 1 February 1977.
considerable percentage. Because the air temperature in which snow crystals grew, did not exceed $-21^\circ C$ as shown in Fig. 3, it is assumed that the hexagonal plates grew in cold temperature regions (below $-21^\circ C$).

The percentage of peculiar or unsymmetrical type is approximately 2.5% at a constant rate for each trapping height. Therefore, it was confirmed that the peculiar snow crystals were not generated near the surface. The details of peculiar crystals in question are shown in Tables 1 and 2. Groups D, E and B are the main types of peculiar crystals in the observation period of SC-4. In the case of SC-4, groups A, B and E are relatively predominant at higher levels. On the other hand, groups F and G, which show a considerably complex structure in comparison to group E, are slightly predominant at lower levels. In the case of SC-5, the peculiar crystals of groups A and B increased and groups D and E decreased in comparison with the data of SC-4. Considering the growth mode and correlation of peculiar snow crystals (Kikuchi, 1974), it seems that this result may be related to the increase

### Table 1
Number frequency of peculiar or unsymmetrical shapes of snow crystals in the case of SC-4 obtained at seven observation heights.

<table>
<thead>
<tr>
<th>GROUP</th>
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<th>75</th>
<th>100</th>
<th>125</th>
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<tr>
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<td>4</td>
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### Table 2
Number frequency of peculiar shapes of snow crystals in the case of SC-5.

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<td>11</td>
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<td></td>
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<td>1</td>
<td>1</td>
<td>4</td>
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<tr>
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<td></td>
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<td>1</td>
<td>2</td>
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</tr>
<tr>
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<td>1</td>
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<td>3</td>
<td>11</td>
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</tr>
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</table>
of columns and the decrease of bullets in the case of SC-5, as shown in Fig. 6.

4.2 The size distribution of hexagonal plates and single bullets, and the growth mode of columns

Following analysis were carried out on the case of SC-4, in which good results were obtained in the replicating condition of snow crystal sondes. In this case, surface air temperature at the observation site was \(-31.0^\circ\) (at 1137 LMT) and \(-31.2^\circ\)C (at 1203 LMT). Therefore, it is assumed that the air temperature ranges of lower atmosphere, in which the snow crystals were observed, were \(-31.0\) to \(-31.5^\circ\), considering the vertical distribution of temperature in Fig. 3.

As seen in Fig. 5, hexagonal plates coexist with other types of snow crystals at a percentage of 20 to 30, constantly. The size distribution of hexagonal plates is shown in Fig. 7, at each trapping height \((H)\). In this case, such crystals were relatively small in the size range than that of the case observed by Ono (1969). The mean values \(\bar{d}\) of the diameter of hexagonal plates gradually increase with the decrease of trapping height and the maximum size of crystals also increases with the decrease of height except for surface datum. Regarding those facts, it seems that those crystals grew during their descent through the cloud base near the surface.

Fig. 8 is the frequency distribution of the length \((l)\) of \(c\)-axis of all single bullets, sampled in the case of SC-4. In this figure, open circles indicate the data for the single bullets at the Ishikari Plain in Hokkaido observed by Kikuchi (1968). The data of present observation are distributed in the narrower and smaller ranges of \(l\), in comparison with the result of Kikuchi. The frequency distribution of the axial ratio \((c/a)\) of all single bullets in the case of SC-4 is shown in Fig. 9. In this figure, open circles indicate the data for the single bullets observed by Kikuchi (1968). The data obtained from present observation tend to distribute in the narrower and smaller region of \(c/a\). According to the facts described above, it is assumed that the bullet type crystals in this observation grew in the
limiting layer of snow clouds or ice saturated layers.

Examination of the growth mode of columnar crystals has been carried out by many researchers. As described above, Kikuchi (1968) mainly dealt with single bullets and combination of bullets. Iwai (1973) also examined the growth mode of columnar crystals. Such crystals which were examined in surface observations were relatively large in the size range of the c-axis of crystals than in the present case. On the other hand, Ono (1969, 1970) studied the shape, riming properties and growth mode of snow crystals in natural clouds. According to his data, the length of c-axis of warm and cold region columns is approximately the same as in the present case. Kikuchi and Hogan (1978) treated columns of diamond dust type, with a somewhat shorter size range than in the present case. Recently, Sato et al. (1981) observed the snow crystals at Amundsen-Scott South Pole Station, Antarctica and concluded that the region of growth of

Fig. 9 Frequency distribution of the axial ratio (c/a) for all single bullets, sampled in the case of SC-4.

Fig. 10 Relation between the length of c-axis (l) and a-axis (d) of all columns in the case of SC-4.
columnar type crystals, as introduced by Ono (1969), should be extended to longer regions of $a$-axis.

The relation between the length of $a$-axis ($d$) and $c$-axis ($l$) of all columns in the case of SC-4 is shown in Fig. 10. In this figure, dotted lines indicate the region for the columns in natural clouds observed by Ono (1969), a solid line the empirical relation for the columns at the ELK Mountain orographic clouds observed by Auer and Veal (1970) and broken lines the limits for the columns at South Pole Station observed by Sato et al. (1981). The data of present observation are nearly coincident with that of Sato et al., except some of the longer regions of $d$.

Fig. 11 is the frequency distribution of the length ($l$) of $c$-axis at each trapping height. In this figure, $\bar{l}_c$ and $\bar{l}_b$ are the mean values of $l$ for columns and single bullets, respectively. $N_c$ and $N_b$ mean the total number of columns and single bullets, respectively. In general, it is clear that those mean values gradually increase with the decrease of trapping height ($H$). This fact suggests that the columnar crystals grew during their descent through the lower atmosphere near the surface. Therefore, it seems that there was a enough amount of water vapor from which the crystals grew in the atmosphere at a height of a few tenths meters to about several hundred meters locally, although the present observation height was in a lesser saturation condition with respect to ice as seen in the data of routine sounding of Fig. 3. As a part of moisture source,
there is a possibility of advection from the town site of Inuvik by the easterly wind in the morning (see, Figs. 1 and 3). In arctic and subarctic regions, it is well known that the moisture comes from man-made sources such as power plants, exhausts from heating plants, automobiles, etc. (e.g., Ohtake, 1967, 1970).

The frequency distribution of the axial ratio \((c/a)\) of columns and single bullets at each trapping height is shown in Fig. 12. In this figure, \((c/a)_{c}\) and \((c/a)_{b}\) are the mean values of \(c/a\) of the columns and single bullets, respectively. Those mean values show a very gradually increase with the increase of trapping height and are approximately coincident with both types of columnar crystals, but it was noted that the large axial ratios are predominant in columns.

5. Considerations

As is evident from Figs. 7 and 11, there are appreciable spreads of crystal sizes, probably because of the different growth time of crystals and the inhomogeneities of moisture in the parent cloud. However, it seems that the hexagonal plates and columnar crystals grew during their descent through the cloud base near the surface, as described in section 4.2.

In order to discuss the mass growth rate of snow crystals distinctly, crystals (25\% of \(N\) at each trapping height) larger than the upper quartile were selected and the mean values of sizes and axial ratios were calculated (see, Figs. 13 and 14). In Fig. 13, broken lines are best fit lines for the columns and the hexagonal plates at each trapping height. What is evident from this figure is the columns and the hexagonal plates grew during their descent. On the other hand, the change of length of \(c\)-axis and axial ratio for the single bullets are relatively small, as seen in Fig. 14.

Calculation was made on the mass growth rate of columns at the condition of \(-31^\circ C\) and 1,020 mb, assuming the constant falling velocity during the descent from 100 to 50 m in height. The relation of mass to the dimension of columns has been derived by Higuchi (1956) in the following form,

\[
m = 1.3a^2l
\]

where \(m\) is the mass in milligram, \(a\) a half of the length of \(a\)-axis and \(l\) the length of \(c\)-axis in millimeter. According to this empirical formula and Fig. 13 (broken lines), the mass growth was \(5.0 \times 10^{-4}\) mg during the descent from 100 to 50 m in height. Falling velocity (25 cm·sec\(^{-1}\)) was estimated from the diagram of Kajikawa (1971), based on the mean axial ratio (2.2) and mean length (310 \(\mu\)m) of \(c\)-axis of columns. Therefore, the calculated mass growth rate of columns was \(2.5 \times 10^{-9}\) g·sec\(^{-1}\).

It is difficult to calculate the mass growth rate of hexagonal plates, at present, because the thick-
Fig. 14 The change of mean axial ratio \((c/a)\) versus mean size of columnar crystals larger than the upper quartile at each observation height.

Fig. 15 Experimental values on the mass growth rate of snow crystals. The growth time (sec) are shown in the side of marks. The growth is at water saturation, except the results of Yamamoto et al. (1952) and present authors.

Fig. 16 A comparison of the experimental values of crystal mass with the theoretical values obtained by Miller and Young (1979). It can be seen that the mass growth rate at a certain temperature increases with the growth time and there is a relative maximum crystal mass near \(-15^\circ\text{C}\), a lesser maximum near \(-5^\circ\text{C}\) and a relative minimum near \(-10^\circ\text{C}\). Those two maxima mean dendritic and needle growth, respectively.

The mass growth rate of columns estimated from the present observation was larger than that found in cold chamber experiment by Yamashita (1974) and in field observation by Kikuchi and Hogan (1979), at the cold temperature regions. On the other hand, this growth rate was similar to that obtained in field experiment by Isono et al. (1956), but larger than that found in cold chamber experiments by Mason (1953), Fukuta (1969) and Ryan et al. (1976), at the warm temperature regions. It is suspected that the large mass growth rate of present observation at the cold temperature regions is caused by the larger crystal size or mass than the cases of Yamashita (1974) and Kikuchi and Hogan (1979), as seen in Fig. 16.
6. Concluding remarks

This paper deals with the observation of snow crystals at a few hundred meters above the surface by means of snow crystal sondes (Magono and Tazawa, 1966). The results from the analysis of typical data obtained on 1 February, 1977 during our Arctic expedition (Magono, 1978) are summarized as follows.

The peculiar or unsymmetrical shapes of snow crystals were involved constantly amount to about 2.5% of the total number in the height from the surface to 150 m. The growth mode of columns was similar to that of columnar type snow crystals obtained by the observation at Antarctica (Sato et al., 1981). The mean values of diameter and the maximum size of hexagonal plates gradually increased with the decrease of trapping or observation height. The length of c-axis of columns and single bullets also increased with the decrease of observation height. Those facts suggest that the hexagonal plates and columnar crystals grew during their descent through the cloud base near the surface. The estimated mass growth rate of columns was $2.5 \times 10^{-9}$ g·sec$^{-1}$ and was similar to that obtained in field experiment by Isono et al. (1956), but larger than that obtained in field observation by Kikuchi and Hogan (1979) and in cold chamber experiment by Yamashita (1974), at cold temperature regions.

From the results described above, it seems that as one possibility, there was an enough amount of water vapor from which the snow crystals grew in the atmosphere at a height of a few tenths meters to several hundred meters locally around the observation site. A part of the moisture may be brought from the man-made sources near the observation site.

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雪結晶ゾンデによるカナダ北極圏の下層大気中における雪結晶の観測

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カナダ北極圏の下層大気中における雪結晶の観測が、雪結晶ゾンデを用いて行われた。1977年2月1日の観測結果をもとに、各観測高度における雪結晶の数と形、角度と角柱状結晶の粒度分布、-21°Cから-31.5°Cまでの温度条件下における角柱の成長様式などが解析された。

その結果、いわゆる奇形雪結晶は、地上から150 mまでの高度において、各高度での結晶総数の約2.5%程度定常に含まれていた。卓越結晶形は、角柱、単砕破、交差角板および砕破集合であったが、角板も相当な割合で観測された。

角柱の成長様式は、Sato et al. (1981)によって報告された、南極点基地での観測結果に近かった。

角板と角柱状結晶の大きさの平均値は、観測高度の低下について徐々に増加した。このことは、結晶を成長させ得る程度の水蒸気が、局地的により観測点近くの地上から数百 mの高さに存在していたことを示している。

角柱の成長速度は、-31°Cで2.5×10^{-9} g·sec^{-1}と計算された。これは、Kikuchi and Hogan (1979)による-35°Cにおける野外観測の値と、Yamashita (1974)による-26°Cにおける室内実験の値より大きかった。この不一致の原因は、観測された結晶の大きさまたは質量の差によると考えられる。

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