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Snow Crystal Observations in Summer Season at Amundsen-Scott South Pole Station, Antarctica*

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Abstract

Snow crystal observations were carried out, using a polarizing microscope, at Amundsen-Scott South Pole Station, Antarctica during January, 1975. Upper air analysis indicated that on all the days with snowfalls there were inversion layers aloft, lower than 550 mb, typically around 600 mb. Saturation or subsaturation was present within these layers. All the days with no snowfalls were accompanied by steep surface inversions alone. Generally, there are no visible clouds corresponding to the saturation layers aloft around 600 mb; For this reason, these snowfalls are called cloudless or "clear sky" precipitation. It was hypothesized that the presence of saturated layers aloft was a necessary factor for clear sky precipitation, but that such saturation could occur and not be accompanied by precipitation at the surface.

A saturated layer aloft is a necessary condition for the formation of precipitation; however, such saturated layers can exist without forming clouds or precipitating, in the absence of active nuclei. Several dry ice seeding experiments were conducted on days with no precipitation to verify the presence of such saturated layers. Dry ice pellets were attached to a tethered balloon, and allowed to slowly rise over the station. Glaciation of the saturated layer was achieved at levels as low as 20 m above the surface; very distinct ice crystal plumes, which often persisted to the horizon, were found between 100 and 150 m above the surface.

Naturally occurring ice crystals were collected on precipitation days, and rapidly examined before appreciable sublimation occurred. Several "peculiar" shapes of snow crystals were detected. The *c*-axis of these crystals, and their crystal structure were defined by polarization microscopy. Several new questions, relative to ice crystal growth mechanisms, arise from the study of these crystals.

Polarization microscope analysis of the naturally occurring precipitation showed the presence of peculiar shapes of snow crystals, and defined their *c*-axis and crystal structures. Several new questions arise from the study of other snow crystals.

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1. Introduction

There has been recent interest in the origin of polycrystalline and peculiarly shaped snow crystals. These exist, in addition to the classical shapes of spatial dendrites, radiating assemblages of dendrites and combination of bullets, and the "Gohei shape" in certain conditions. Interesting characteristics have been reported concerning the structure of spatial dendrites, radiating assemblages of dendrites and combination of bullets. Examination of these crystals under polarization microscopy allows determination of the orientation of the *c*-axis. The angles between the *c*-axes of plates in radiating assemblages of dendrites, the angle between the *c*-axes of the main crystal and its branches in the case of spatial dendrites, and the angle between the *c*-axes of neighboring columns in the case of combinations of bullets have been measured by this technique. An angle of 70° between *c*-axes is most commonly found, when the frequency distribution of these angles is analyzed1),2).

Peculiar external shapes3),4),5),6) attracted attention when observed by ordinary transmitted light microscopy. A principal axis and a growth mechanism were developed based on typical and basic shapes of snow crystals. Although some of these peculiar shapes were discovered around the Sapporo, Hokkaido, Japan area; recently, the ratio of the peculiar shapes to other "classical" shapes was one percent or less5),8). Furthermore, the surface air temperatures were very warm, 0°C～–10°C when they were observed. Therefore, these peculiar shapes observed at Hokkaido were thought to be an exceptional case. They originated at lower air temperature conditions (lower than –25°C) at around 550 mb or higher within a deep humid layer accompanied by strong cyclonic flow.

A few reports of the results of snow crystal observations at stations in the Antarctic continent have been previously published9),10),11). Almost all the shapes of snow crystals reported there were minute columns and hexagonal plates, or relatively long columns and bullets. Shimizu reported a special case12) of the length of the columns. Kikuchi and Yanai6) reported an observational result by means of replication method of snow crystals during the traverse from Syowa Station to the South Pole and return, covering a period from September 1968 to February 1969, in the South Pole region. Although the main shapes of snow crystals observed by them were bullets and columns as expected, in air temperatures of –26°C～–30°C, a few examples of peculiar shapes reported by Kikuchi3),4),5) previously were discovered.

Almost all observations of ice and snow crystals on the Antarctic continent described above were obtained in conjunction with other programs. A frequent and careful series of observations of ice and snow crystals was accomplished, to attempt to obtain more exact information about these peculiar shapes. This paper describes the results of snow crystal observations using a polarization microscope, and is especially addressed to peculiar shapes, observed during the austral summer season at Amundsen-Scott South Pole Station, Antarctica.

2. Techniques employed

The geographical altitude of Amundsen-Scott South Pole Station is 2804 m and the mean surface air temperature in January is approximately -30°C. Extended periods occur during the latter part of the austral summer season, when spontaneous nucleation in the free atmosphere can occur.

Radiosonde observations are made twice (00, 12Z) daily at the station, during the summer season, using conventional sondes and a GMD receiver. The low temperatures, and extremely dry air found near the surface, limit the accuracy of humidity measurement; calculation from radiosonde data often indicate that air saturated with respect to ice, and sometimes with respect to liquid water, is present as a result of Katabatic return flow in the 650–550 mb region. The presence of these saturated layers was verified by dry ice seeding during these experiments.

Precipitating ice crystals were collected near the station, at the entrance to the helium storage hut. This hut was unheated and had a natural snow floor. This allowed examination of the collected crystals almost en vivo, without significant sublimation or melting during the short period between collection and examination. The nucleating mechanism responsible for ice crystal initiation at temperatures warmer than -40°C is not known.

A polarizing microscope was used to take color photographs of the shape of snow crystals, and to determine the *c*-axis of the crystals, at approximately 10-minute intervals. Simultaneously, falling snow crystals were collected by sedimentation and replicated on 25×75 mm glass slides coated with 0.5% Formvar solution at 5 or 10 minute intervals, and small "diamond dust" crystals were collected by both sedimentation and interception techniques. These replicas were used to estimate the relative rate of precipitation intensity and the rate of spatial distribution of crystal shapes.

3. Results

3.1 Meteorological conditions

Figure 1 shows the sounding curves obtained when snow crystals were observed, in the latter part of January. One can see from this figure that there is always strong surface inversion and an additional inversion layer aloft at around 600 mb (about 800 m above snow surface). Relative humidities at the surface are hard to evaluate, but are usually between 20 and 40%. Above the surface inversion layers, the relative humidities increased to 80% (with respect to water) or more on all days. The relative humidities often became saturated with respect to water adjacent to the inversion layer at 600 mb. Above the 600 mb level, the distributions of the relative humidities were quite variable. It is worthwhile to note that there were saturated or subsaturated layers between the 650 mb and 600 mb heights, invariably, whenever there was snowfall. Therefore, it is probably that supercooled cloud droplets were nucleated under spontaneous or heterogeneous conditions and grew to ice or snow crystals. Generally, there are no visible clouds at this level, leading to the classification of these snowfalls as cloudless or "clear sky"

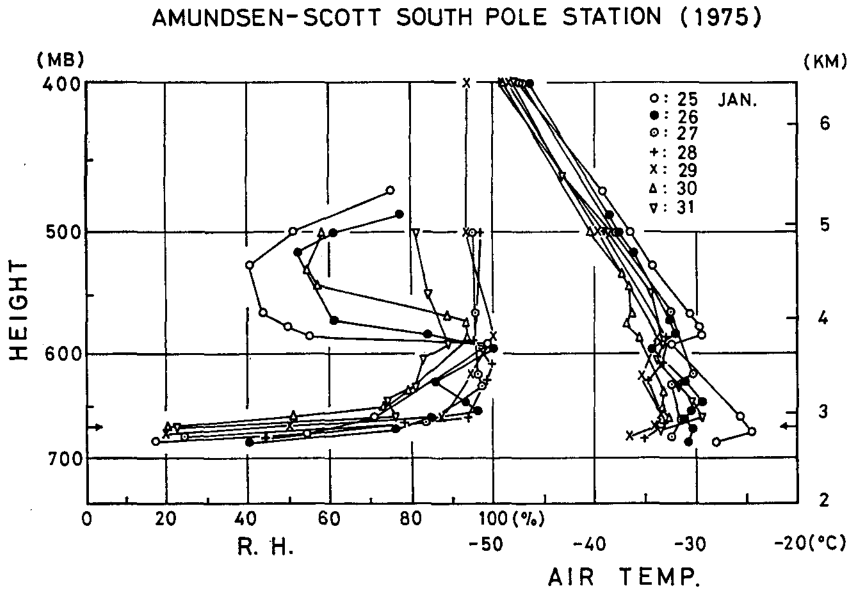


Fig. 1 Sounding curves obtained during periods when ice crystal precipitation was occurring.

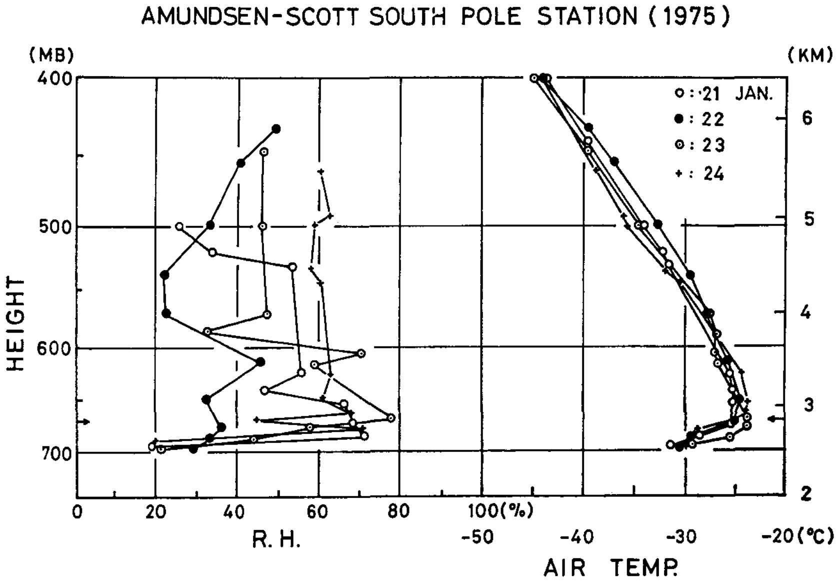


Fig. 2 Sounding curves obtained during periods when no ice crystal precipitation occurring.

precipitation. Sounding curves obtained when no snowfalls were observed in the latter part of January are shown in Fig. 2. In this figure, the slope of the surface inversion is greater than the cases of Fig. 1. There were no inversion layers around 600 mb in any of these cases. Relative humidities near the surface were between 20 and 30% and did not differ from the snowfall cases; the near surface inversion layers were accompanied by higher humidities, increasing to 80% with respect to water. These values are nearly the same as in the snowfall cases; however, at 600 mb, in some cases, the relative humidities did not reach ice saturation.

A comparison of the temperatures, relative humidities and mixing ratios obtained from the radiosonde ascents on "no snowfall days" (22 and 24 January) and "snowfall days" (25 and 26 January) is shown in Fig. 3. The values of the absolute humidities show nearly the same tendency in vertical distributions, but the vertical profiles of relative humidity are very different, especially at the 600 mb level. Saturation with respect to water in the cases of the 25th and 26th would be a result of the colder temperatures in the same layer. Contrasted with the water saturation layer, there were very dry layers of

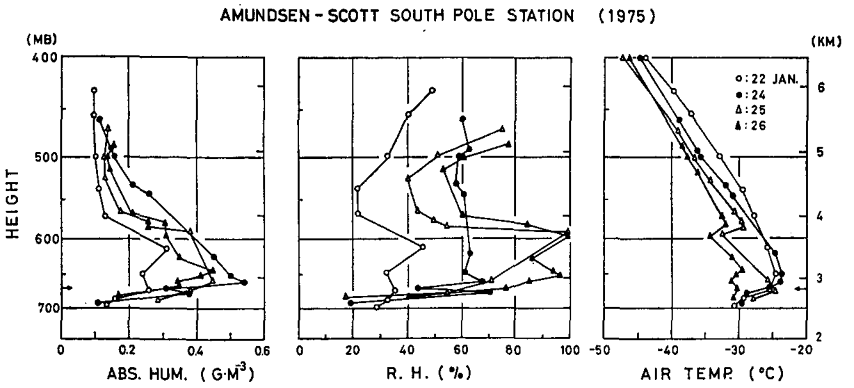


Fig. 3 Comparison between sounding curves obtained during presence and absence of ice crystal precipitations.

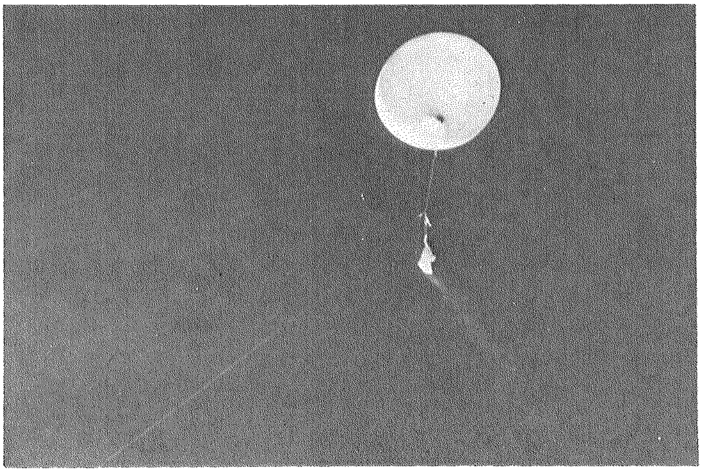
from 40% to 60% relative humidity at around 550 mb. This dry layer would be a result of the warm temperatures above 600 mb level.

To verify the existence of the saturated or subsaturated layers between 650 mb and 600 mb, we performed seeding experiments using dry ice pellets suspended from a tethered balloon at the same place where we collected snow crystals on glass slides. The seeding experiment carried out on the 17th January 1975, nucleated a glaciation trail, 20 m above the snow surface. The glaciation trail became more active above the 130 m level as seen in Fig. 4. About one hour later, upon recovery of the tethered balloon, fine icing deposits were found on the tethered string, indicative of saturation aloft.

About one-half an hour after our seeding experiment was completed, a C-130 airplane took off from the station area. As soon as the airplane took off, a streak of contrail appeared. The contrail remained over the station more than three hours, and then diffused into an altostratus cloud (all of these observations verify the existence of a saturated layer just above the surface, which became a visible cloud when nucleated).

During the observation period, ice crystal precipitation occurred on 11, 12, 13, 14, 18, 20, 25, 26, 27, 28, 29, 30, 31 January and 1 February. The amount of snowfall was practically unrecordable, and generally noted as "trace" in routine station observations. The crystals precipitating on the 12, 26 and 29th were "diamond dust" type.

The sequence of the vertical temperature profiles from the snow surface to the 400 mb level during the observation period from 00 L.M.T. at the 11th



(a)

(b)

Fig. 4 Seeding experiments using a tethered balloon.
(a) The first glaciation trail was recognized at 20 m above snow surface.
(b) The glaciation trail had became more active above 130 m level.

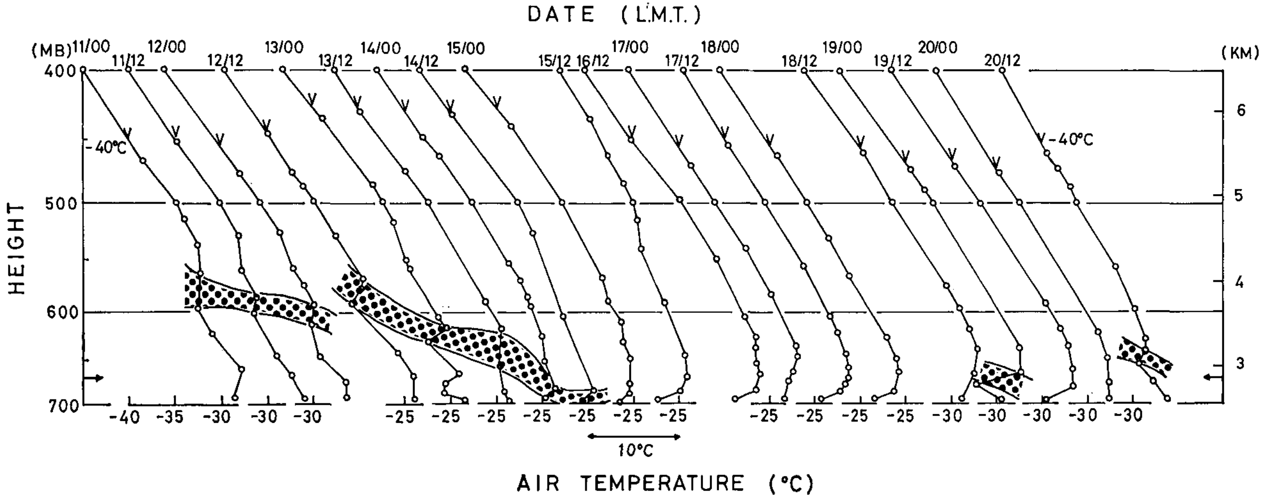


Fig. 5 Time sequences of temperature profiles from 00LMT 11 to 12 LMT 20 January 1975. (Dotted shadings show extent of inversion layers aloft and hooks on each temperature curve indicate height of –40°C level)

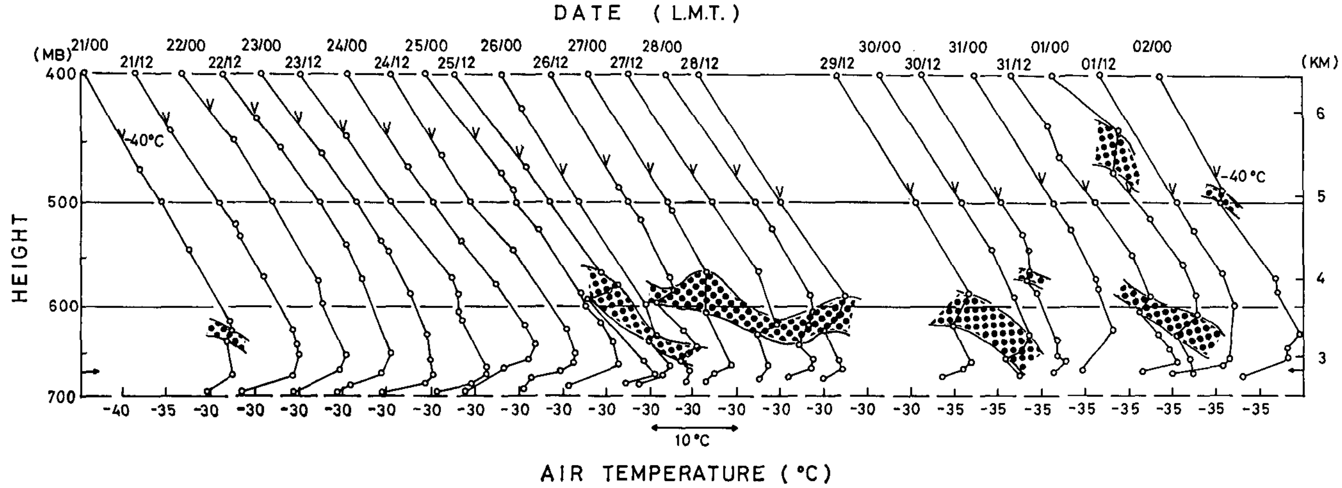


Fig. 6 Time sequences of temperature profiles from 00LMT 21 January to 00LMT 2 February 1975. (Dotted shadings show extent of inversion layers aloft and hooks on each temperature curve indicate height of –40°C level)

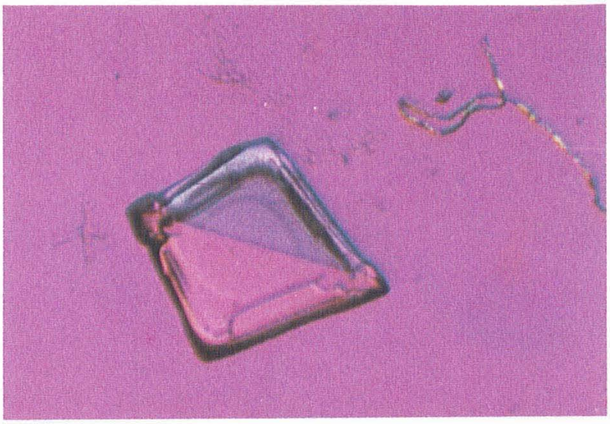


Fig. 7 An extended prism planes of rectangular form with bullets observed at 1531 LMT 12 Jan. 1975. (×120)

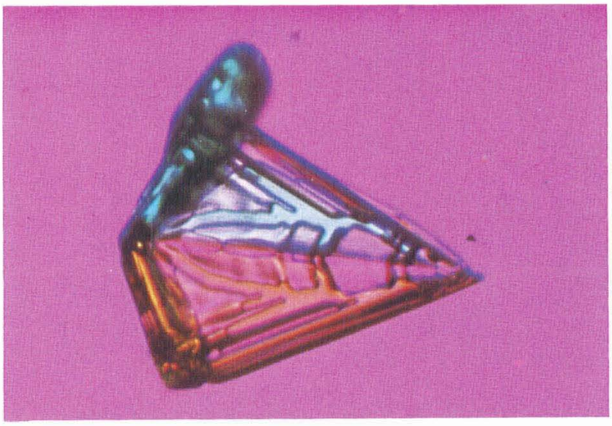


Fig. 8 An extended prism planes of rectangular form with bullets observed at 1243 LMT 13 Jan. 1975. (×104)

Fig. 9 An extended prism planes of pentagonal form with bullets observed at 1030 LMT 26 Jan. 1975. (×126)

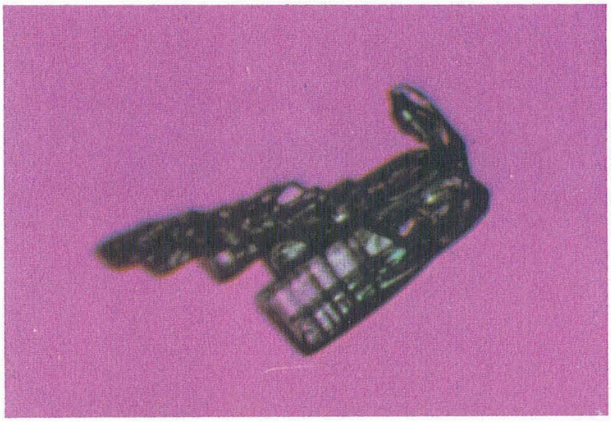


Fig. 10 An assemblage of multiple bullets along a growth axis observed at 1330 LMT 30 Jan. 1975. (×118)

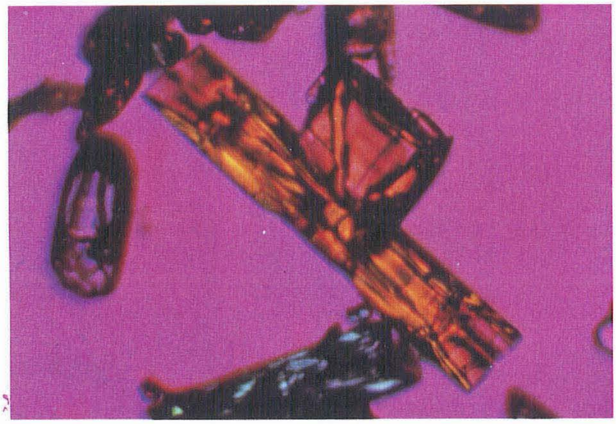


Fig. 11 One kind of combination of bullets but single crystal observed at 1020 LMT 12 Jan. 1975. (×100)

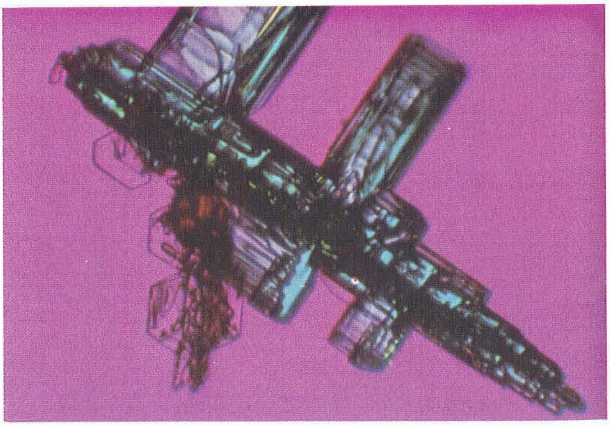


Fig. 12 One kind of combination of bullets but single crystal observed at 1545 LMT 28 Jan. 1975. (×79)

January to 00 L.M.T. at the 2nd February are shown in Figs. 5 and 6. Inversion layers aloft (above the surface inversion at each sounding), are shown by dotted shading. Attention is directed toward the coincidence of snowfall days with inversion layers aloft. The time gradient of the height of the inversion layers aloft, is indicative of a subsidence inversion. Generally, the subsident velocity of the inversion aloft is approximately 1 $\mathrm{cm \cdot sec^{-1}}$ under an anticyclonic condition. In these cases, the lowering rate is 1000 m per day or two, equivalent to a subsident velocity of 1.2 $\mathrm{cm \cdot sec^{-1}}$ to 0.6 $\mathrm{cm \cdot sec^{-1}}$, which is of the proper order, to be due to such subsidence.

Hogan[11]) emphasized the existence of cirrus bands at higher altitude (above the saturation layers), during precipitation periods. It was hypothesized that small ice crystals, from these cirrus, settle into the saturated layers, serving to nucleate columnar ice crystals which then precipitated to the surface. During this observation period, the routine meteorological report indicates the presence of cirrus bands in the second layer on 17, 18, 20, 25, 26, 27, 28, 29, 30 and 31 January. The direct correlation between surface snowfall and the existence of cirrus clouds was not fully investigated, as continuous observations of cloud cover and precipitation were not obtainable. Analyses of the data obtained during the austral summer of 1975 indicates that an inversion layer aloft (ie above the near surface inversion) always accompanies "clear sky" precipitation. Previous studies of similar precipitation phenomena at Verkhoyansk, Siberia by Клинов[15]) and at Byrd Station, Antarctica by Shimizu,[12]) did not report similar inversions aloft, but only the steep near surface inversion.

3.2 *Polarization microscope analysis*

Previous observations of snow crystal form at Syowa Station were carried out using transmitted light microscopy. At Amundsen-Scott, a polarizing microscope was set up in a sheltered but unheated area, so that precipitating ice crystals could be collected and rapidly examined before melting or subliming. About 600 color photographs showing the form, and polarization planes of freshly collected ice crystals were collected during the experiment period. This polarization technique can be used to immediately determine the crystal structure of frozen precipitation[13]).

Fig. 7 shows one of the peculiar shapes of natural snow crystals observed. This type of snow crystal was named "extended prism planes of rectangular form with bullets" by one of the authors[14]); however, Kobayashi et al.[16]), recently termed it a "twinned scroll," these names have not been adopted and are only tentative. This optical system can easily detect the *c*-axis of snow crystals under a sensitive color plate, that is to say, when the color is yellow the *c*-axis is directed from upper left to lower right and when the color is blue the *c*-axis is from upper right to lower left. This specimen is in very early stage of crystal growth, and is very thin, so the yellowish color is not distinct, but only shifted slightly away from the pink color of the sensitive color plate. However, it is clear this specimen is a polycrystalline snow crystal although the two included bullets or scrolls are obscure. Fig. 8 shows the same type crystal as Fig. 7. Here the two bullets are distinctive and yellow color of half area of the crystal is more clear than in Fig. 7. Furthermore, another snow crystal appearing the corner of this figure is of columnar shape, so there is no mistake in selecting the direction of the *c*-axis of this peculiar shape. Recently Kobayashi et al.16) proposed that some of the crystals of peculiar shapes may be explained as "twins". According to them, these crystals (as shown in Figs. 7 and 8) are equivalent to the early stage of a "linear assemblage of twinned columns and scrolls" of Fig. 15 in their paper16) or Photos. 6 and 25 in Kikuchi's papers4),5). Fig. 9 shows a simple example of "extended prism planes of pentagonal form with bullets". At one time, it was considered that this crystal consisted of three single crystals from consideration of the external crystal structure, however, as we interpret this picture, the crystal is a polycrystal consisting of two parts. The blue portion is of rectangular form but differs in shape from Figs. 7 and 8. The line which divides in two parts of the blue portion is not grain boundary; the blue portion is a single crystal and may be an "inside plate", first described by Yamashita17). An "assemblage of multiple bullets along a growth axis" or a "linear assemblage of doubly twinned prisms"16) is shown in Fig. 10. The parallel arrangement of up and down sides of columns or bullets identifies them as single crystals. Similar crystals were observed at Syowa Station; but could not be uniquely identified in transmitted light. Recently, Kobayashi et al.16) presented a growth mechanism based on a "ribbon growth" suggested by Wagner18) and Chalmers19) for a "linear assemblage of twinned columns and scrolls." In the case of a "linear assemblage of doubly twinned prisms," they have been considered to grow in the same manner as in the case of a "linear assemblage of twinned columns and scrolls," beside containing two adjacent twin planes along a "trunk".

The four crystals described above are one kind of peculiar shapes of snow

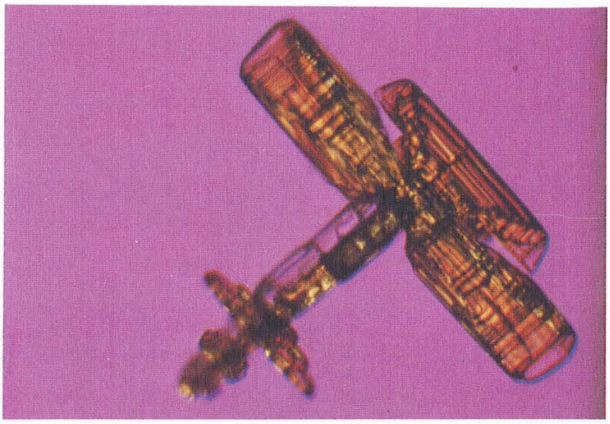


Fig. 13 One kind of combination of bullets but single crystal observed at 1530 LMT 26 Jan. 1975. (×57)

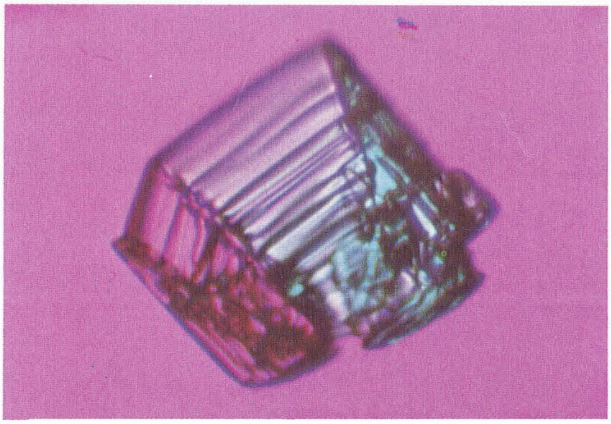


Fig. 14 A single columnar scroll but polycrystal observed at 1330 LMT 26 Jan. 1975. (×120)

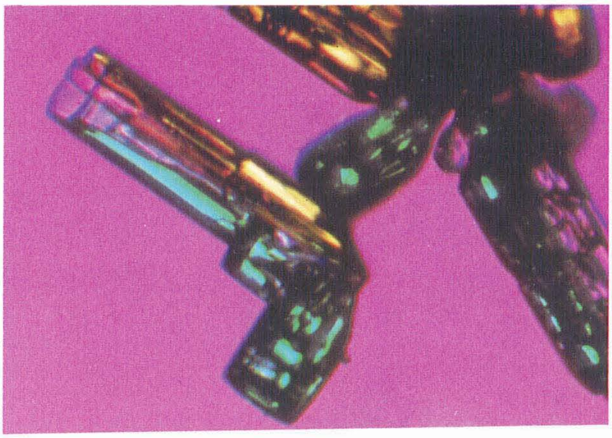


Fig. 15 A combination of bullets but a bullet showing upper left is a polycrystal observed at 1123 LMT 26 Jan. 1975. (×112)

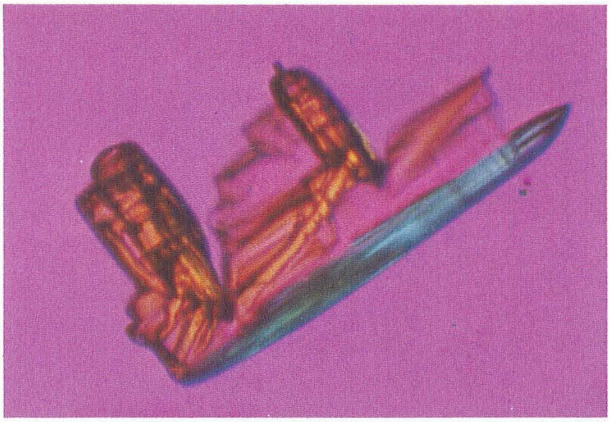


Fig. 16 One kind of combination of bullets observed at 1333 LMT 26 Jan. 1975. (×118)

Fig. 17 A peculiar crystal structure and shape of snow crystals observed at 1624 LMT 13 Jan. 1975. (×76)

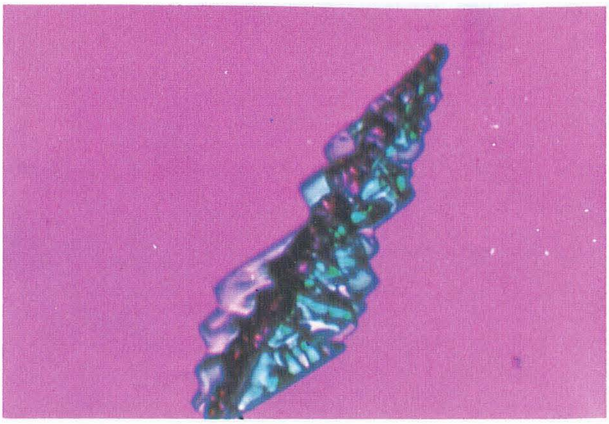


Fig. 18 A peculiar shape of snow crystals observed at 1406 LMT 13 Jan. 1975. (×68)

crystals. Figs. 11～13 seem to be a "combination of bullets" type of crystal. As we know, the "combination of bullets" is one of the most typical polycrystals; however, the crystals shown in Figs. 11～13 were a single crystal each, as determined from the monocolor. Fig. 11 may be estimated to be a "combination of bullets" consisting of three bullets if there is not a square form of a prism plane in contact with two columns or bullets, under usual transmitted light microscopy. Subsequently, a question arises to the direction of the *c*-axis of the square form, that is to say, whether the *c*-axis is parallel to the crystal directed from upper left to lower right or upper right to lower left. While the direction of the *c*-axis of the crystal is directed from upper right to lower left, it is different from the direction estimated from crystal form; the direction of the crystal is the same as the direction of the crystal directed from upper left to lower right as definite a yellow color. The direction of the *c*-axis of the square form is the same as the crystal directed from upper left to lower right. That is to say, the crystal shown in Fig. 11 is considered as a polycrystal of the combination of bullets from the external shape. Fig. 12 is a different combination of bullets. It has been considered that each bullet grows from a center nucleus or a supercooled frozen cloud droplet[20), for that reason, each bullet grows radially outward from the center. In this picture, the scalelike side planes seen in the lower left are another crystal. On the contrary, in the crystal shown in Fig. 12, each bullet or column grows parallel to each other, not radially. The direction of the *c*-axis of each column is from upper right to lower left entirely. Last in question is the crystal directed from upper left to lower right corner. The direction of the *c*-axis of this crystal is the same in each column as estimated from blue color in this case. Therefore, this crystal is not a long column having its *c*-axis directed from upper left to lower right, but several short columns or thick plates having *c*-axis directed from the upper right to lower left, connected to each other in chain like fashion from upper left to lower right. This is a single crystal, although the external shape is more complicated. A similar example of this growth mechanism is shown in Fig. 13. The crystal with shape similar to an old style airplane is a single crystal, also. The direction of the *c*-axis is the same as the main bullets, from upper left to lower right, as estimated from a yellow color. A propeller like crystal at the extreme right side is a "twin columnar scroll" in the terms of one of the authors[14). Crystals of this "twin columnar scroll" type were frequently observed at Syowa Station. The twin columnar scroll may be the result of disintegration of the type of crystal shown in Fig. 13.

The crystal shape as shown in Fig. 14 is a "single columnar scroll". As shown previously, a twin columnar scroll is a single crystal of the same origin as a column or bullet. A single columnar scroll is generally considered a single crystal; however, the color contrast shown in Fig. 14 indicates this single columnar scroll is a polycrystal. The direction of the *c*-axis of this type of crystal is expected from upper left to lower right in general, from consideration of its external shape. Contrary to expectation, however, the crystal is a polycrystal and moreover the *c*-axis is at a right angle (as shown in blue color) to the direction expected. Fig. 15 seems to be a simple "combination of bullets", consisting of two bullets. Actually the bullet of short length is a single crystal having a *c*-axis parallel to the external shape of the bullet. The long bullet is not a single crystal according to the color contrast. The direction of the *c*-axis of the long bullet is the same as that of the short bullet, from upper right to lower left. Therefore, it is possible that the long bullet is not bullet but a scroll which has the same crystal structure as described in Fig. 14. A polcrystalline snow crystal which has a different external shape but nearly the same crystal structure as Fig. 15 is shown in Fig. 16.

Figs. 17 and 18 show examples of newly found types of peculiar shapes. Although Fig. 17 shows a simple shape externally, it is a polycrystal due to its color contrast.

In general, the sizes of the peculiar shapes of snow crystals observed at the South Pole Station were smaller than found in previous observations3),4),5). It is assumed that the height of the saturation layer was lower and thinner than the previous cases, making less water available during the crystals growth period.

4. Concluding Remarks

Snow crystal observations, utilizing a polarizing microscope were carried out at Amundsen-Scott South Pole Station, Antarctica from the 9th of January to the 4th of February 1975. During this period snowfalls occurred from the 11th to 14th and from the 25th to the 31st. Additional brief periods of ice crystal precipitation were observed. From the upper air analysis, all the days of snowfalls were accompanied by inversion layers aloft, but lower than 550 mb. Saturated or subsaturated layers corresponded with these inversion layers. A time history of the height of these inversion layers aloft, indicates that the inversion is a subsidence inversion and the subsident velocity is approximately

1 cm·sec^{-1}. Previous work by one of the authors[11)] resulted in a hypothesis that the existence of cirrus bands at higher altitude above the saturation layers is an important factor initiating snow crystal falls. Small ice crystals settling into the saturated layers serve to nucleate columnar ice crystals which then precipitate to the surface. The direct correlation, however, between surface snowfall, and the existence of cirrus bands was not thoroughly investigated during this period. Hogan[21)] pointed out from his aerosol observations at McMurdo, Siple and South Pole Stations in the summer season of 1974 that aerosol concentrations of 50~100 cm^{-3} are observed quite regularly during the Antarctic summer on the Polar plateau; however, a lowering of the tropopause and strong subsidence was accompanied by aerosol concentrations of 500~1000 cm^{-3} of very small mean size. He considered that the high concentrations observed concurrent with a lowering of the tropopause are likely to result from chemical reactions between ozone and organic or other convertible vapors transported from drier upper levels with the increased water vapor available near the surface. Considering that the saturated or subsaturated layers aloft (around 600 mb) have air temperatures warmer than –40°C, that is to say, in the range of the heterogeneous nucleation, it may be possible that the lowering of the tropopause, and the accompanying subsidence of these and other aerosols, glaciated the supercooled water droplets existing in the layers around 600 mb.

"Peculiar" shapes of snow crystals were observed and defined by their *c*-axis and crystal structures, through polarization microscopy. Although snow crystals with the form of "extended prism planes of rectangular form with bullets"[14)] or "twinned scroll[16)], and an "assemblage of multiple bullets along a growth axis"[14)] or a "linear assemblage of doubly twinned prisms"[16)] were clearly understood as a polycrystal and a single crystal respectively using a polarization microscope, new questions arise from other snow crystals observed, for example, single crystals as shown in Figs. 11, 12 and 13, and polycrystals as shown in Figs. 15 and 16. Further, as shown in Figs. 17 and 18, new types of the peculiar shapes were discovered through these observations. Growth of formation mechanisms of these peculiar shaped crystals has remained unknown until recently. Kobayashi et al.[16)] have applied the twinning structure theory to polycrystalline types of snow crystals. Presently, it has been considered that the types of a "twinned scroll", "linear assemblage of twinned columns and scrolls" and "linear assemblage of doubly twinned prisms and scrolls" are explained by a twinning structure.

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