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On the Confluent Phenomena of Radar Echoes

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Abstract

The confluent phenomena of radar echoes were observed during the period of special observations on heavy rainfall at the northwestern area of Kyushu Island. The process of the confluent phenomena of radar echoes was clarified by analyzing the data. That is to say, it was recognized that the difference in movement speeds of echoes is due to the formation of new echo cells.

As two clouds which were different in growth stage merged with each other, after the confluence the clouds became colloidal unstable and large rain drops were formed rapidly. Namely the cloud physical processes changed with the confluence.

1. Introduction

It is well noted on the radar scope that band-shaped echoes merge or intersect frequently on the occasion of heavy rainfalls (e.g. Imakado and Tsutsumi, 1966 ; Kato et al., 1977). And it was reported by Obana (1976) that the confluences of echoes corresponded to the peaks of rainfall intensity respectively during a heavy rainfall and the peaks occurred at about 10~20 minutes after the confluence of echoes.

The phenomenon was explained as follows. Obana (1976) considered that an echo joined another echo according to the different movement directions and speeds of echoes which were moved by the different wind directions and wind speeds because of the difference in each echo height. On the other hand, Kato et al. (1977) proposed the idea that the phenomenon was caused by the confluence of the air flow at the same height.

As the confluent phenomenon means the organizing of precipitation clouds to cluster, it is important on the formation of clouds which result in heavy rainfalls. Nevertheless no analytical results which describe detailed three dimensional structures of radar echoes at the time of confluence are available.

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Thus it has not been clarified whether the height of each echo is actually different each other or whether the movement of the echo is equal to that of cells composing each echo at the time of confluence.

The confluent phenomenon results in the interaction between two types of clouds, but it is not clear how the confluent phenomenon essentially affects the formation of rainfall. And it is observed frequently during heavy rainfalls, thus it may be considered that it is one of the important phenomena on the formation of heavy rainfalls. Therefore, the purpose of this paper is as follows. Based on the details of the horizontal and vertical sections of radar echoes, the real image of confluent phenomenon including the three dimensional structures and movements of both echoes at the time of confluence will be clarified. In addition, based on the time changes of cloud physical variables before and after the confluence, the essential effect on the rainfall formation of the confluent phenomenon will also be clarified.

2. Observation

Cooperative observations on heavy rainfall were carried out by Hokkaido University, Nagoya University and Kyushu University at the northwestern area of Kyushu Island during the period of June to July 1984 where a special network was set up with radars, rawinsondes and so on, as shown in Fig. 1. The confluent phenomenon of radar echoes was observed on 25 June 1984 during the observational period by the radar of Hokkaido University which was set up temporarily at Mt. Kokuzo in Saikai Town. The output data of this radar are shown as the forms of digital values of equivalent radar reflectivity factor on the grids of $1\text{ km} \times 1\text{ km}$ on the horizontal plane of every 0.5 km in height and on the grids of $1\text{ km} \times 0.5\text{ km}$ on the vertical plane with arbitrary directions. The following analyses are based on these data and the PPI pictures of radar at Mt. Seburi operated by Fukuoka District Meteorological Observatory.

The meteorological situation was as follows. The Baiu front was stationary over the central to northern area of Kyushu Island on 24 to 25 June, but it was moving up in a northerly direction when the confluent phenomenon of radar echoes was observed. The confluent phenomenon described in the following sections was observed in the radar echoes associated with the Baiu front.

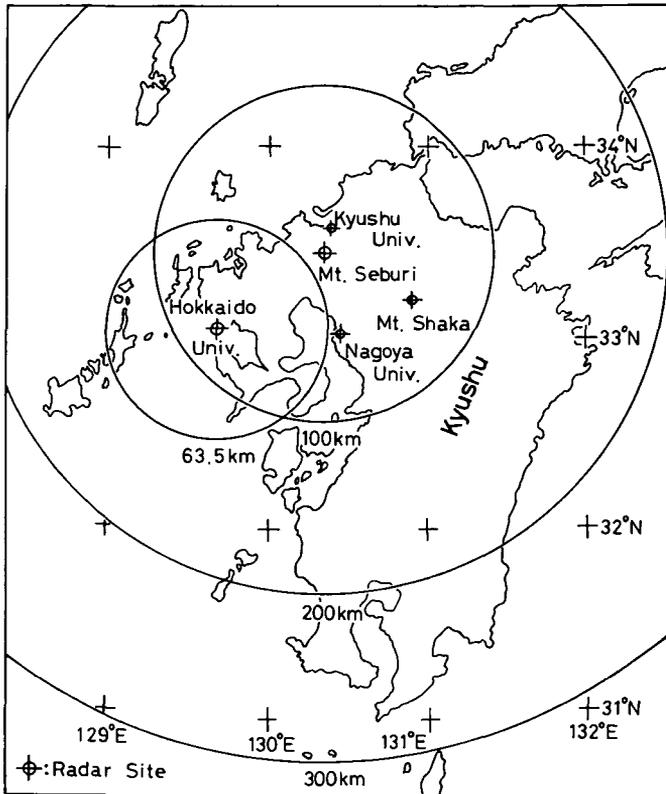


Fig. 1 Observation area and radar sites.

3. Three dimensional structures of radar echoes at the time of the confluence

At first PPI pictures of radar are analyzed in the same manner as in other studies. Fig. 2 shows the time sequence of PPI pictures obtained by the radar at Mt. Seburi. The range marks are drawn every 50 km on these pictures. It is seen from this figure that echo A moved toward the east and at about 1040 JST joined echo B which hardly showed the movement. As far as we see the time sequence of the PPI pictures, the confluent phenomenon in question seem to occur owing to the difference in movement speeds of echo A and echo B.

Next, the time sequence of high resolution CAPPI displays at 4 km in height obtained by Hokkaido University radar is shown in Fig. 3 in order to study this phenomenon in detail. So as not to overlap with each echo, the figure is

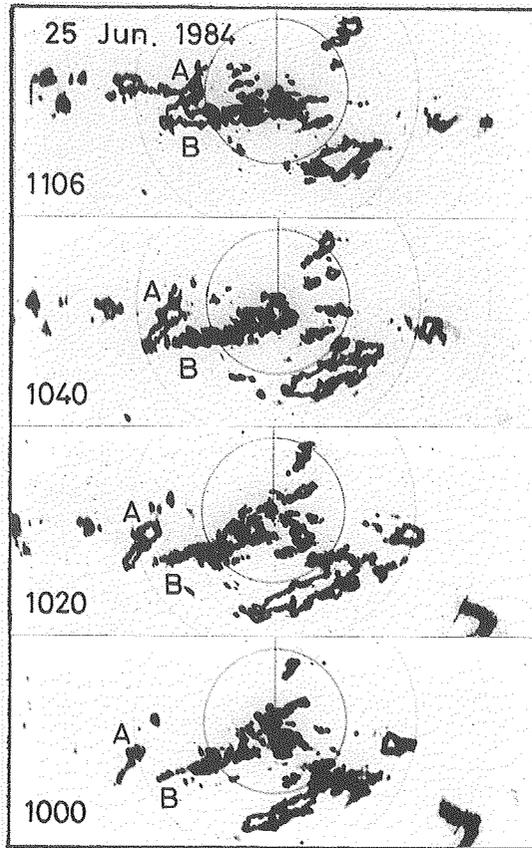


Fig. 2 PPI pictures obtained by the radar at Mt. Seburi. Range marks are drawn every 50 km.

represented in a manner in which the positions of radar site at each time are shifted vertically at equal intervals. So the mutual positions of echoes at different times are not represented correctly in a south-north direction but are represented correctly in an east-west direction. The contours of CAPPI displays are drawn at 20, 25, 30 and 35 dB(Z) in radar reflectivity factor, and PPI displays (more than 15 dB(Z)) of 1.1° in elevation angle are superimposed by dotted lines on the CAPPI displays at 1000 and 1040 JST. In the figure, the corresponding echo cells are connected by solid lines. As the vertical axis represents time and the horizontal axis indicates the distance along the east-west direction respectively, the inclinations of the solid lines represent the movement speed of the echo cells along the east-west direction. Judging from

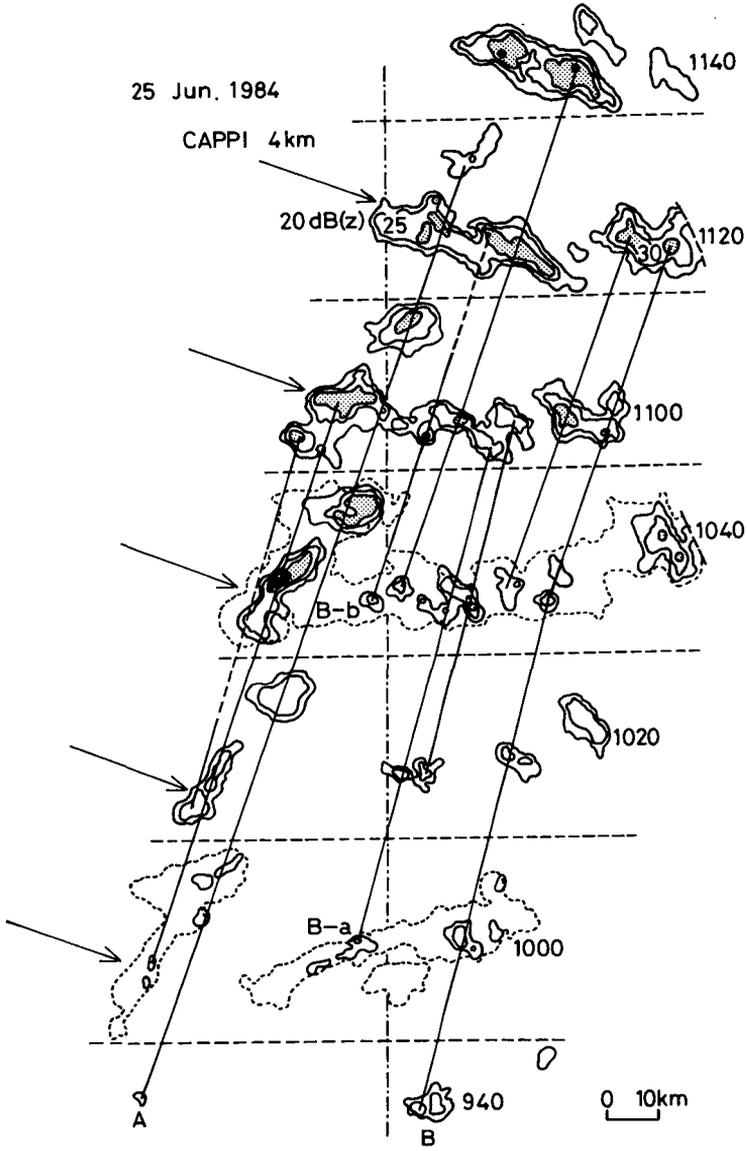


Fig. 3 Time sequence of CAPPI displays at 4 km in height obtained by Hokkaido University radar. Dotted lines describe PPI displays of 1.1° in elevation angle.

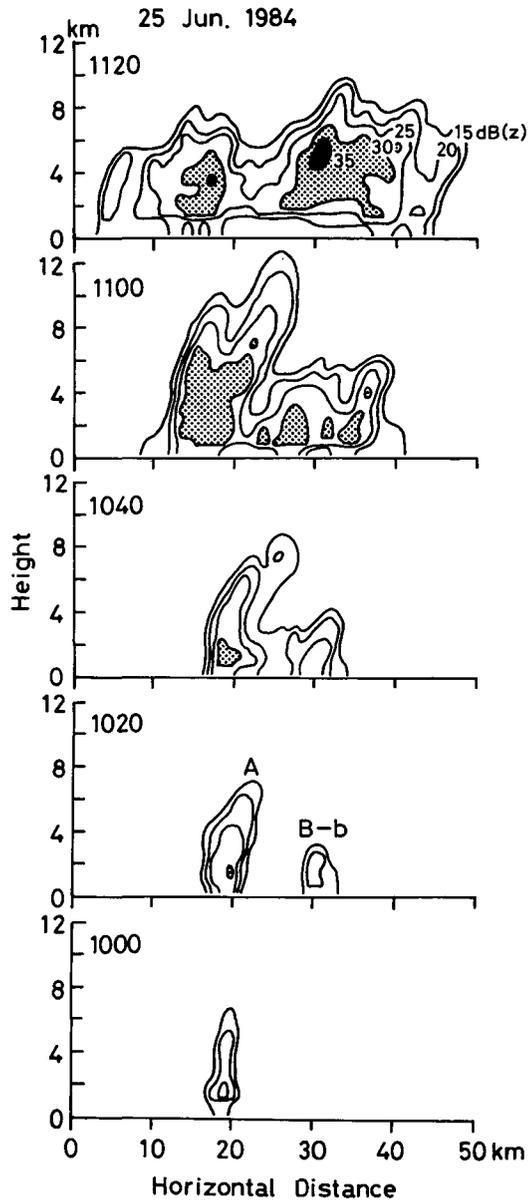


Fig. 4 Time sequence of vertical sections along the arrows in Fig. 3.

the fact that solid lines are in parallel with one another, it is recognized that each echo cell is moving with almost equal speed. Therefore, echo A should not join echo B originally, because echoes A and B are constructed from echo cells with equal movement speed. Nevertheless, echo A joined echo B. Thus the reason for the confluence is as follows. Since new echo cells are formed continuously at the western end of echo B, echo B seems to be stationary. On the other hand, echo A is moving with the same speed as the movement speed of echo cells. The result is that echo A joins echo B. Namely, it is considered that the confluent phenomenon owing to the difference of movement speed is caused by the apparent difference of movement speed of echoes in spite of the equal movement speed of echo cells.

The vertical sections along the arrows in Fig. 3 are shown in Fig. 4. Contours of 15, 20, 25, 30 and 35 dB(Z) are drawn in this figure. It is seen from this figure that echo cell B-b which appeared at about 1040 JST in CAPPI display at 4 km in height was formed in the lower layer at about 1020 JST and grew to join echo A at about 1040 JST. Though the height of each echo top is different actually at the time of confluence, it is considered that the difference in height did not cause the confluence through the difference in movement speed but the apparent difference of movement speed caused the confluence mentioned above. After the confluence, a strong portion in intensity more than 30 dB(Z) spreaded rapidly and then a new echo cell B-b grew into the larger echo instead

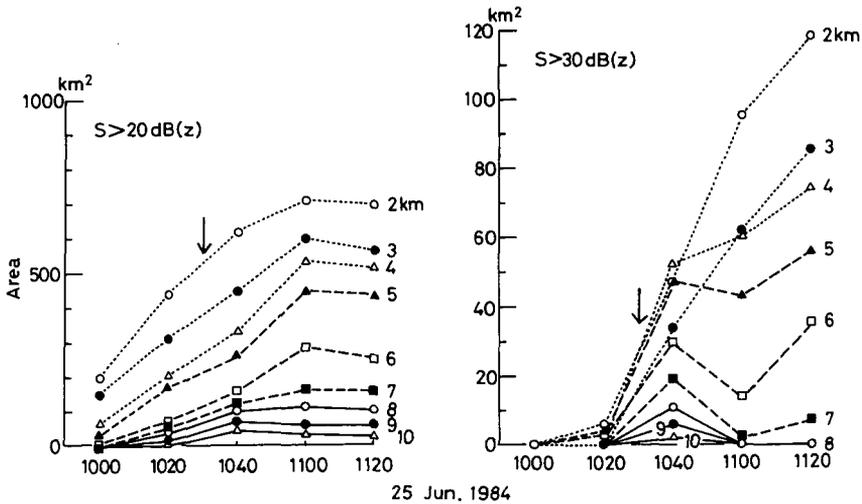


Fig. 5 Time changes of areas with more than 20 dB(Z) and 30 dB(Z) in radar reflectivity factor at each height. Arrow shows the time of confluence of echoes.

of echo A.

4. Time change of radar reflectivity factor before and after confluence

In this section, the phenomena occurring after confluence were studied following the process of confluence in the preceding section. First, we analyzed the time change of the areas of echoes A and B-b at each height. Fig. 5 shows the time changes of areas with more than 20 dB(Z) and 30 dB(Z) in radar reflectivity factor. In this figure the arrow indicates the time of the confluence of echoes. It is seen in left-hand figure that the areas with more than 20 dB(Z)

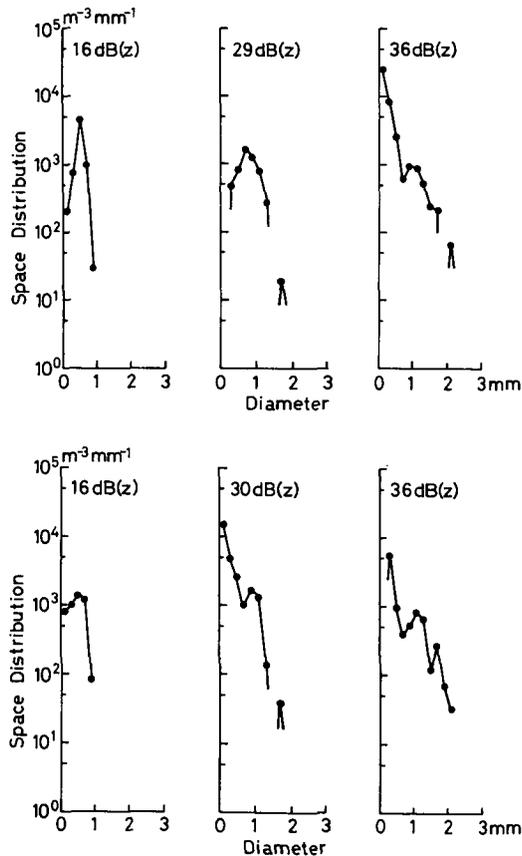


Fig. 6 Size distributions of rain drops observed at the ground.

continue to enlarge with time although the values differ at each height. And it is important that the increase rates do not change before and after the confluence.

But, it is seen in the right-hand figure of Fig. 5 that the increase rates of areas with more than 30 dB(Z) change drastically after the confluence. Then, the echo in the lower layer maintains a large increase rate although the echo in the upper layer decreases. As it is considered that the radar reflectivity factor more than 30 dB(Z) indicates the existence of larger rain drops, from a viewpoint of rain drop formation the right-hand figure may be explained as follows. In the case where two clouds that are different at the growth stage join each other, the clouds become colloidal unstable owing to the different size distribution of rain drops contained in the clouds and larger rain drops are formed rapidly. As a result, the areas with more than 30 dB(Z) spread rapidly.

Fig. 6 shows the size distributions of rain drops observed at the point which is about 20 km distance from the place of occurrence of the confluent phenomenon. The ordinate and abscissa are the space distributions and diameter of rain drops respectively. It is seen that there are rain drops of 2 mm or more than 2 mm in the case of 30 to 35 dB(Z) with regards to radar reflectivity factor whereas there are only rain drops less than 1 mm in the case of approximately 15 dB(Z). It is considered that from this degree of difference in size distribution of rain drops the clouds become colloidal unstable and larger rain drops are formed rapidly (e.g. Shiotsuki, 1974). Therefore it is appropriate to explain the rapid increase rate of area with more than 30 dB(Z) in Fig. 5 by the colloidal unstable theory.

5. Concluding remarks

The confluent phenomena of radar echoes were observed and examined in detail. It was clarified from the analysis that the confluent phenomena owing to the difference of movement speed are caused by the apparent difference of movement speed of echoes in spite of the equal movement speed of echo cells. The apparent difference of movement speed based on the fact that one echo seems to be stationary, because new echo cells are formed continuously at the western end of the echo. After the confluence, the cloud physical process changed. This can be explained as follows. Clouds become colloidal unstable owing to the different size distributions of rain drops contained in the clouds and large rain drops are formed rapidly when two clouds that are different in growth stage join each other. In order to confirm this result and clarify the other side

of confluent phenomena, the confluent phenomena must be examined further in the future.

Acknowledgments

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In Situ Growth Experiments of Snow Crystals of Low Temperature Types Observed at Inuvik in Arctic Canada

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Abstract

Growth experiments of snow crystals collected in nature were carried out at Inuvik in the Arctic Canada (68°22'N, 133°42'W) from December 1985 to January 1986 to examine in more detail the structure and growth mechanisms of peculiar shaped snow crystals. The results of in situ growth experiments were summarized as follows; 1) Supercooled droplets collected on snow crystals showed pyramidal faces under lower supersaturation and most of them grew in crossed plates at -20°C under higher supersaturation. 2) Crossed plates type crystals showed the successive formation and growth of small plates under the conditions of low supersaturations. 3) In situ growth experiments of peculiar shaped snow crystal showed that the water vapor supply to the tip of crystalline boundary was very important for the condition of growth, and these experimental results provided the information about the boundary structure of the peculiar shaped snow crystals.

1. Introduction

Various kinds of unknown and peculiar shapes of natural snow crystals were reported in the Antarctic continent (Kikuchi, 1969, 1970; Kikuchi and Yanai, 1971). Most of them were polycrystalline snow crystals. The principal axis (c-axis) of several types of such crystals and their crystal structures were decided by polarizing microphotographs (Kikuchi and Hogan, 1976). Kobayashi et al. (1976) attempted to explain the growth mechanisms of some of those crystals with the cubic structure model. The frequency of occurrence of the peculiar shapes in natural snowfalls in the Arctic Canada was examined by Kajikawa et al. (1980). These peculiar shapes of snow crystals were tentatively

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classified by Kikuchi (1974).

On the other hand, artificial experiments to produce peculiar shapes of snow crystals were carried out by Sato and Kikuchi (1983) and Kikuchi and Sato (1984). Various kinds of peculiar shapes of snow crystals reported by Kikuchi were made artificially and the frequency of their peculiar shapes to the common shapes in the relatively low temperature regions, that is, columns, crossed plates, combination of bullets and so on was studied also (Kikuchi and Sato, 1984). Gohei twin crystals which were one of typical peculiar shapes of snow crystals were explained by the introduction of the cubic structure model twice on the basal plane at formation processes by Sato and Kikuchi (1985).

In order to examine in more detail the structure and growth mechanisms of the peculiar shapes, especially gohei twins, growth experiments of snow crystals collected in nature have been carried out at Inuvik in the Arctic Canada ($68^{\circ}22' N$, $133^{\circ}42' W$). This paper will describe the results of the growth experiments of snow crystals observed in Arctic Canada using a small cold chamber mounted on a stage of an inverted polarizing microscope.

2. Experimental method

Observations of snow crystals were carried out at Inuvik in Arctic Canada from December 1985 to January 1986.

Snow crystals collected on glass slides by the sedimentation method were examined by a polarizing microscope. A peculiar shape of snow crystals was selected on the glass slide and was picked up and moved on to a cover glass. The cover glass was moved into a thermal diffusion type cold chamber mounted on the stage of an inverted polarizing microscope.

This chamber was made in such a way as to cool the temperatures of the upper and lower stages in the chamber independently. The two stages were cooled by allowing an electric current to flow through the thermoelectric cooling panels. The heat release sides of the thermoelectric cooling panels were operated at a constant temperature by circulating a coolant at a constant temperature. The temperatures of the cool sides of panels were controlled by the direct electric current.

The temperatures of the upper and lower stages were measured with fine thermocouples attached directly to the surfaces of stages. The surface of upper stage was lined with ice sheets formed by freezing of water for supplying water vapor. Temperatures at the upper and lower stages, T_t and T_b were recorded by a dual channel recorder. Controlling the temperatures of upper and lower

stages, experiments of condensation (growth) and evaporation of snow crystals introduced into the chamber were repeated. The temperature of the lower stage for growth of ice crystals (T_b) was regarded as the growth temperature of snow crystals. The degree of supersaturation was calculated by the temperature difference $\Delta T = T_t - T_b$. The growth of crystals was recorded by taking photographs at appropriate intervals under a microscope. The principal axis (c-axis) of crystals was determined by the use of crossed nicols and a sensitive color plate of the polarizing microscope.

3. Results and considerations

Various kinds of snow crystals in wide ranges of temperature from the dendrite and rimed snow crystals (warm temperature types) to the combination of bullets and columns (low temperature types) were observed in this observation period. Crossed plates type crystals were more frequent than the combination of bullets regarding polycrystalline snow crystals. "Sea gull" type snow crystals were more frequent than the "Gohei twin" crystals which were typical peculiar shaped snow crystals. These were considered to be the result of the difference of the meteorological conditions. Six series of the growth experiments were carried out.

3.1 Frozen cloud droplets

Rimed snow crystals were observed several times under relatively warm temperature conditions during the observation period. Frozen cloud droplets have been considered as one of the sources of the growth of polycrystalline snow crystals (Kikuchi and Ishimoto, 1974). An example of the frozen cloud droplets attached on snow crystals was observed in the afternoon of January 15, 1986. Figure 1 shows the temperature profile on that day. As seen in the figure, the temperature inversion was strong and warm air intruded into the upper layer around 800 mb. In Fig. 1, solid and open circles and a small dot indicate water saturation, subsaturation and below ice saturation, respectively. In this case, therefore, there was a thick water saturation layer above 900 mb level. The water saturation layer, especially from 900 mb to 650 mb level, were available as the formation and growth conditions for dendrites, sectors, and rimed snow crystals. The frozen cloud droplets attached to the snow crystals on this day did not show any distinct crystal planes. It was considered, therefore that the most cloud droplets were attached to the surfaces of snow crystals falling near the ground surface, so that the frozen cloud droplets did not have a sufficient

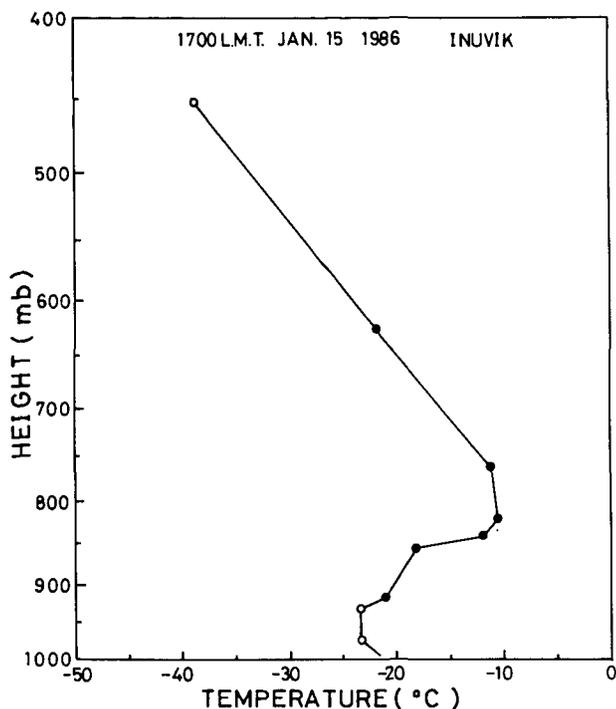


Fig. 1 Vertical temperature profile on 17 L.M.T. January 15, 1986.

growth.

Two examples of frozen cloud droplets on the surfaces of hexagonal plate and broad branched crystals are shown in Figs. 2 and 3, respectively. The scale drawn by bars with spikes at both ends in all photographs of this paper indicates $100\ \mu\text{m}$. A number of frozen cloud droplets having the same sizes were seen on the hexagonal plate (Fig. 2(a)). Figure 2(b) shows a photograph of Fig. 2(a) taken through crossed nicols. The frozen cloud droplets appear in a contrast of white, gray and black colors. The droplets seen in white and gray did not show any distinct crystal planes. The frozen cloud droplets in black, on the other hand, showed distinct crystal planes and they grew as a some polyhedron. Enlarged photographs of the central part of the hexagonal plate are shown in Fig. 2(c) and (d). Six black points shown by arrows in Fig. 2(d) were clear in several frozen droplets. These six black points are considered to be pyramidal planes ($10\bar{1}1$) of each frozen droplet. Further, the small white area surrounded by six black points is considered to be the basal plane (0001) of each frozen droplet. It is known that the pyramidal planes are recognized at the initial

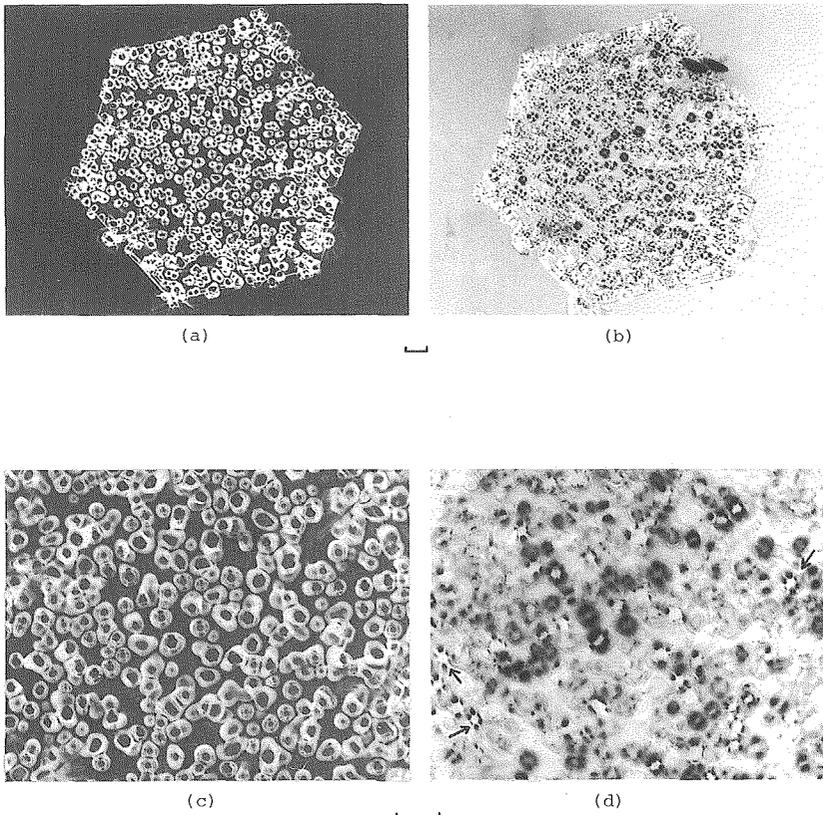
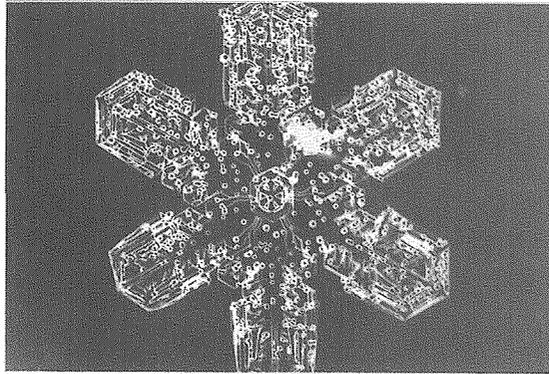


Fig. 2 Microphotographs of frozen cloud droplets on the snow crystal of hexagonal plate.

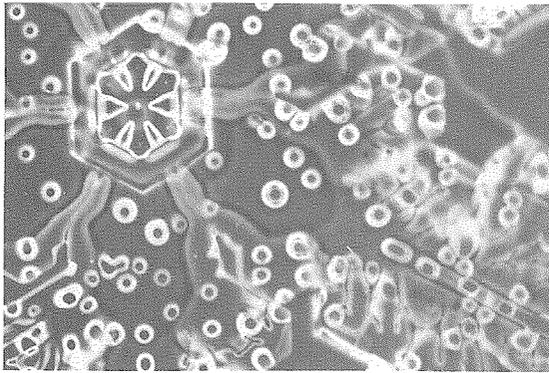
growth stage of frozen cloud droplets when they grow slowly and are in the equilibrium state. Experimental conditions were achieved under conditions of $T_b = -20^\circ\text{C}$ and the temperature difference, $\Delta T = 2^\circ\text{C}$, respectively.

Another example shown in Fig. 3 is also a case of pyramidal planes. In this case, the shape of snow crystal was a broad branched crystal as shown in Fig. 3(a). A number of spheres and polyhedrons were recognized in the central part of the crystal as shown in Fig. 3(b). The black points in Fig. 3(c) as recognized through crossed nicols show the crystal faces formed and grown on the frozen cloud droplets as described in the previous figure.

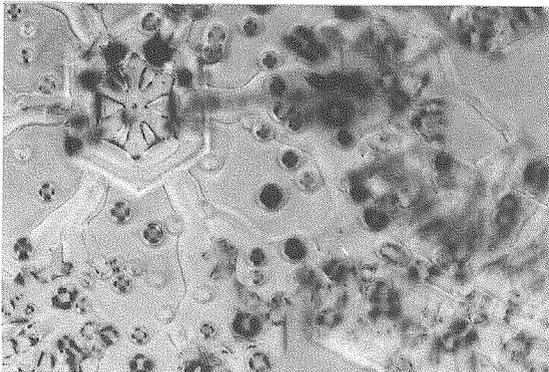
The next growth experiment was made on the frozen droplets on a hexagonal plate which was observed on January 12, 1986. The size of frozen cloud



(a)



(b)



(c)

Fig. 3 Microphotographs of frozen cloud droplets on the snow crystal of broad branched crystal.

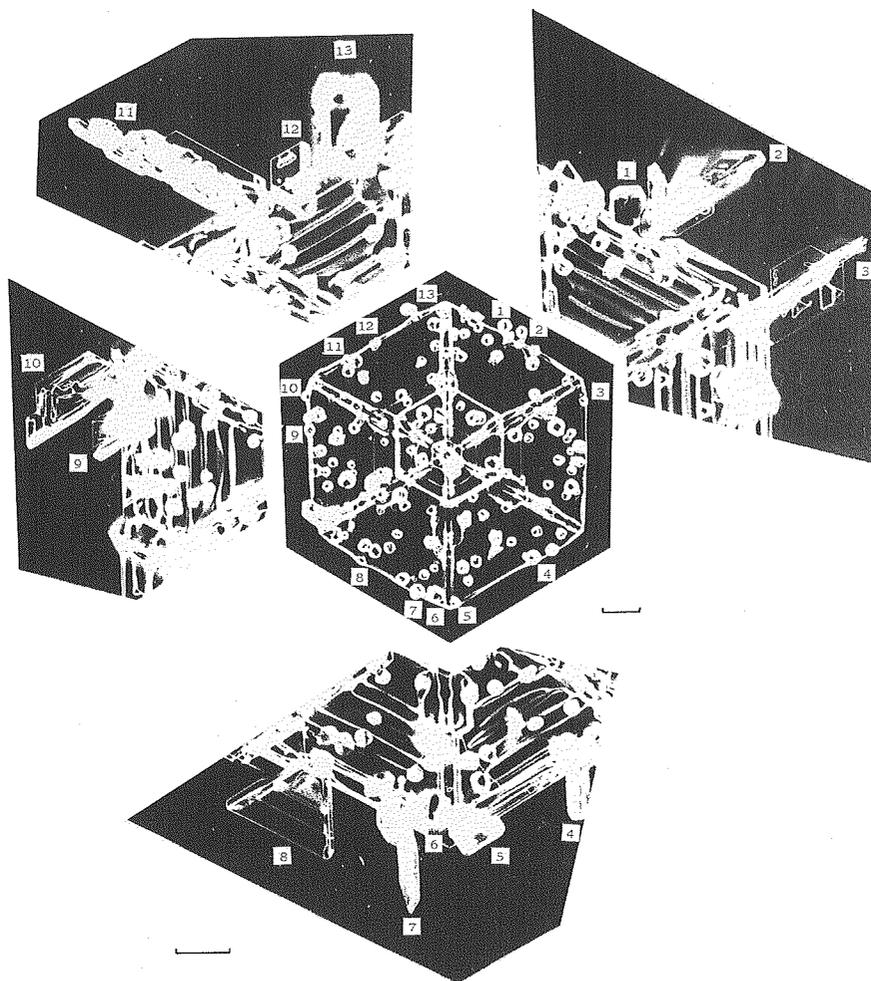


Fig. 4 Microphotographs of frozen cloud droplets on the snow crystal of hexagonal plate and various shapes of crystals which grew from the frozen cloud droplets shown the numerals.

droplets observed at ground surface was from 14 to 50 μm in diameter. Figure 4 shows a hexagonal plate with frozen cloud droplets and various shapes of crystals which grew from frozen cloud droplets at the edges and corners of the plate. Experimental conditions were achieved under the conditions of $T_b = -25^\circ\text{C}$ and the temperature difference, $\Delta T = 4^\circ\text{C}$, respectively. Thirteen frozen cloud droplets at the edges and corners of the crystal were examined. Eight

crystals of them grew as polycrystalline snow crystals and they were of crossed plates, for instance, Nos. 3, 8, and 10. Others grew as single snow crystals and they were columns such as, Nos. 1, 4, and 13, and plate such as No. 7. The frozen cloud droplets, therefore, can be considered to grow to the crossed plates as polycrystalline snow crystals and the columns and plates as single crystals under the temperature conditions of $T_b = -25^\circ\text{C}$ and $\Delta T = 4^\circ\text{C}$.

3.2 Crossed plates

Crossed plate type crystals are one of the typical shapes of snow crystals observed below -20°C . An example of the crossed plates type crystals observed on December 29, 1985 was grown in a cold chamber. In this experiment, $T_b = -30^\circ\text{C}$ was used as the growth temperature, however, the temperature difference, ΔT was changed from 3°C to 11°C . As well known, ΔT is considered as the degree of supersaturation, therefore, the larger the temperature difference, the higher the supersaturation.

Successive photographs of the growth stages of crossed plates are indicated in Fig. 5. Figure 5 (a) indicates the initial stage, (b) at $\Delta T = 3^\circ\text{C}$, (c) at $\Delta T = 6^\circ\text{C}$, and (d) at $\Delta T = 11^\circ\text{C}$, respectively. The typical growth features of crossed plates, namely, the successive formation and growth of small plates at the crystalline boundary were observed when the temperature difference was only small. When the temperature differences were large, individual plates grew large although the crystal grew along the direction of crystalline boundary. When the supersaturations were large, for instance, $\Delta T = 11^\circ\text{C}$ as shown in Fig. 5(d), the individual plates began to grow toward in the direction of right angles to the growth direction up to that time.

Growth rates of the tip of crossed plates were measured from the center of the examined crystal. The results are shown in Fig. 6. The vertical axis shows the length of the tip from the center of the crystal and the horizontal axis shows the lapse of time from a given time. Slopes of solid lines indicate the growth rate at individual temperature difference, ΔT , respectively. As shown clearly in the figure, it is understood that the growth rate increased with supersaturation. From this figure, for instance, the growth rates were $5.4 \times 10^{-2} \mu\text{m/s}$ at $\Delta T = 3^\circ\text{C}$ and $1.4 \times 10^{-1} \mu\text{m/s}$ at $\Delta T = 11^\circ\text{C}$, respectively. Figure 5(e) and (f) shows the difference of growth stages on the same crystal in which the growth conditions were $T_b = -20^\circ\text{C}$ and $\Delta T = 4.5^\circ\text{C}$. The growth rate at the tip of crystal in this case was $6.5 \times 10^{-2} \mu\text{m/s}$. Successive formation and growth of small crystals, however, were not observed. Experiments were carried out under the temperature conditions from the lower limit of -30°C to the upper

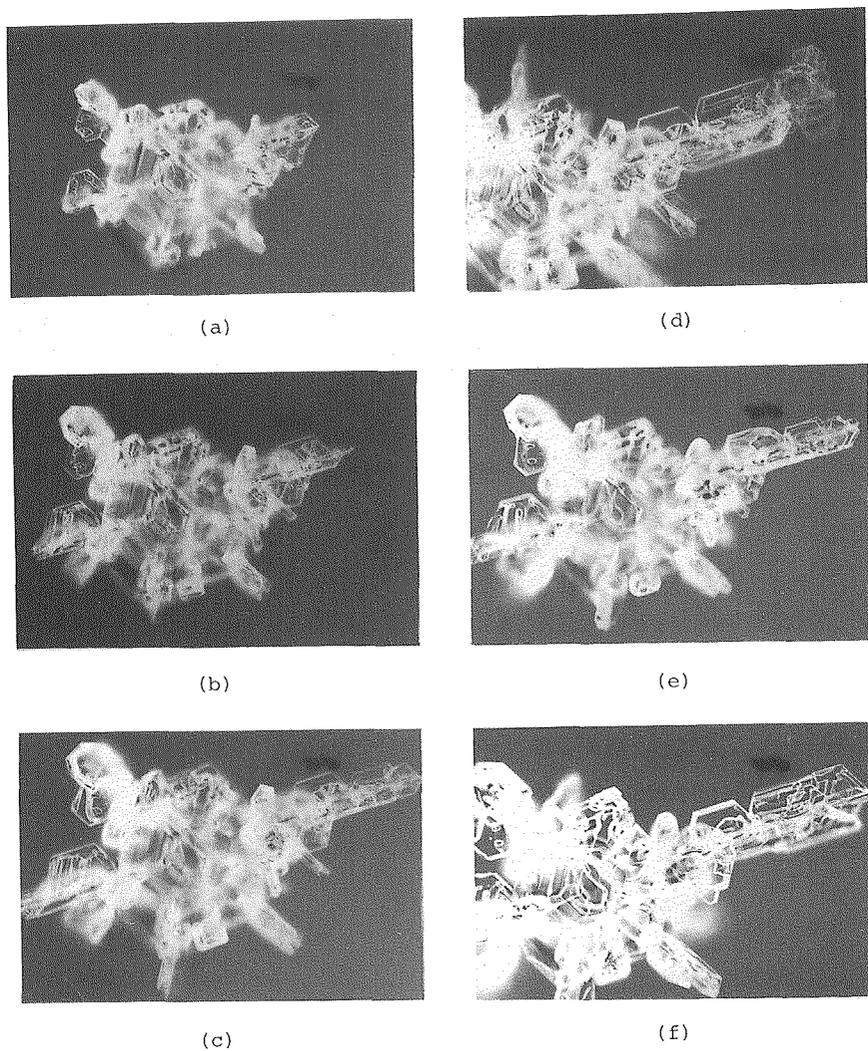


Fig. 5 Successive microphotographs of the growth stages of crossed plates type crystals.

limit of -20°C for the formation and growth of the crossed plates. One of the typical growth features of crossed plates, that is, the successive growth of small plates was not easily observed at the high supersaturation although the growth rate increased with the supersaturation.

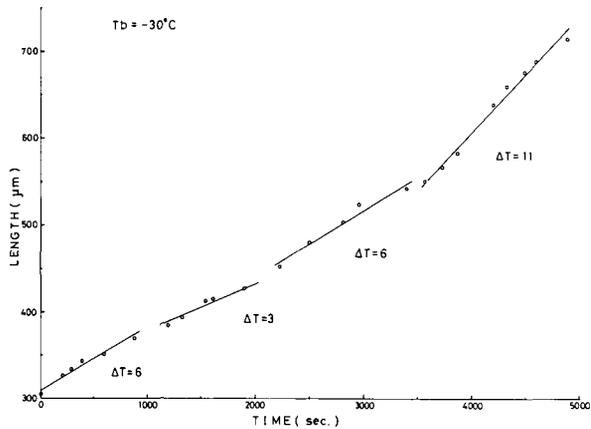


Fig. 6 Length versus time curves (growth rate) at individual temperature differences of crossed plates type crystal.

3.3 Extended prism planes

The remarkable features of peculiar shapes observed in the low temperature conditions are the horizontal growth of the prism planes ($10\bar{1}0$). Growth experiments on extended prism planes were made by two crystals as shown in Fig. 7. Crystal (I) was observed on January 1, 1986 and the crystal (II) was observed on January 17, 1986, respectively. Both crystals (I) and (II) were hollow column or scroll type crystals. Further, a diagonal line on the extended prism plane is recognized in each crystal.

Experiments for crystal (I) and crystal (II) were carried out under the temperature conditions of $T_b = -30^\circ\text{C}$ and $\Delta T = 7^\circ\text{C}$, and $T_b = -30^\circ\text{C}$ and $\Delta T = 3^\circ\text{C}$, respectively. Regarding the crystal (I), the linearly extended prism planes of a single crystal grew as shown in Fig. 7 (I)-(d). On the other hand, regarding the crystal (II), a solid column grew as shown in Fig. 7 (II)-(b). After the evaporation was accomplished, the crystal (II) changed from column to scroll as shown in Fig. 7 (II)-(c). The difference of shapes between these crystals after their growth will be considered to occur from the difference of the humidity conditions or their inherent crystalline structure. Therefore, more experimental data will be required to decide the conditions for the growth of extended prism planes.

3.4 Gohei twins

The most typical "Gohei twin" crystal as shown in Fig. 8 was observed in

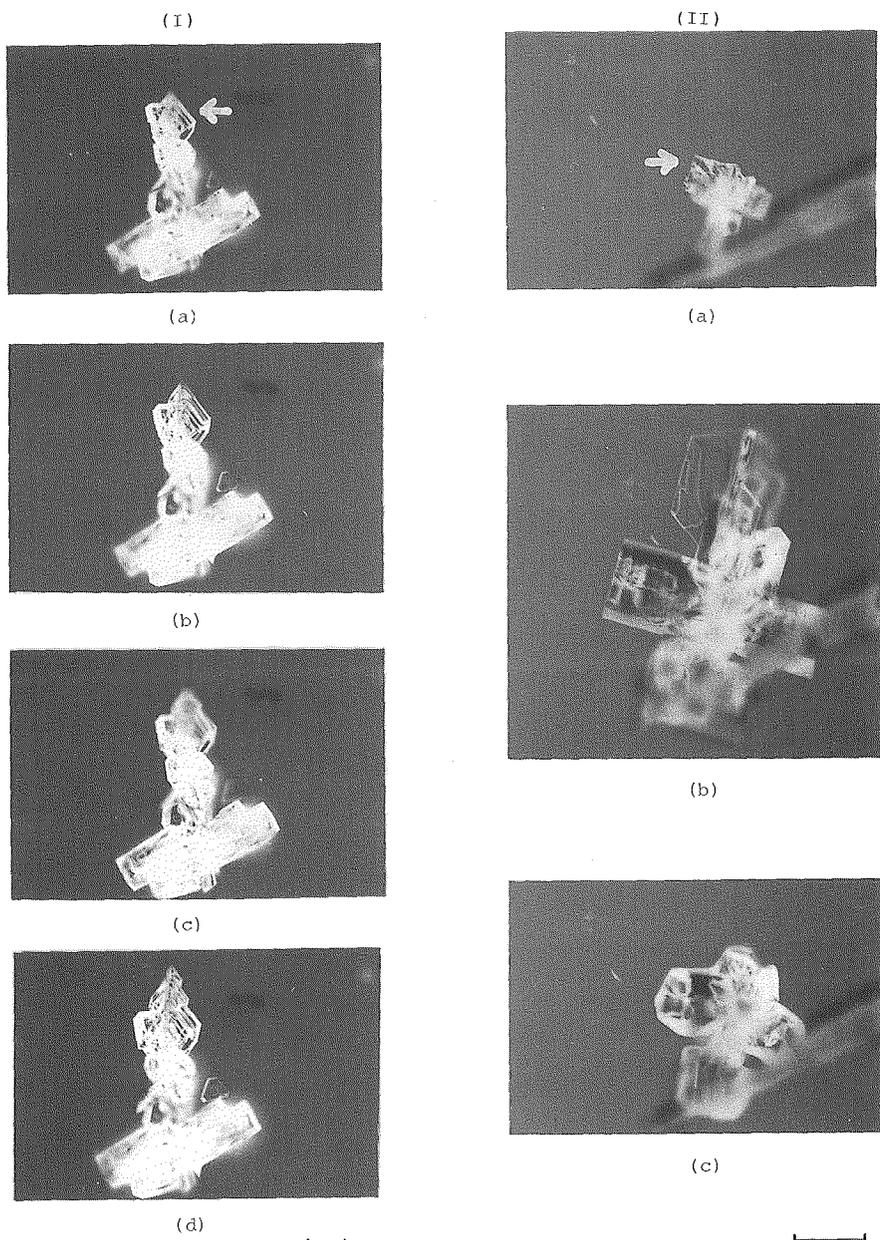


Fig. 7 Successive microphotographs of the growth stages of extended prism planes type crystal. (I) Hollow column, (II) Scroll.

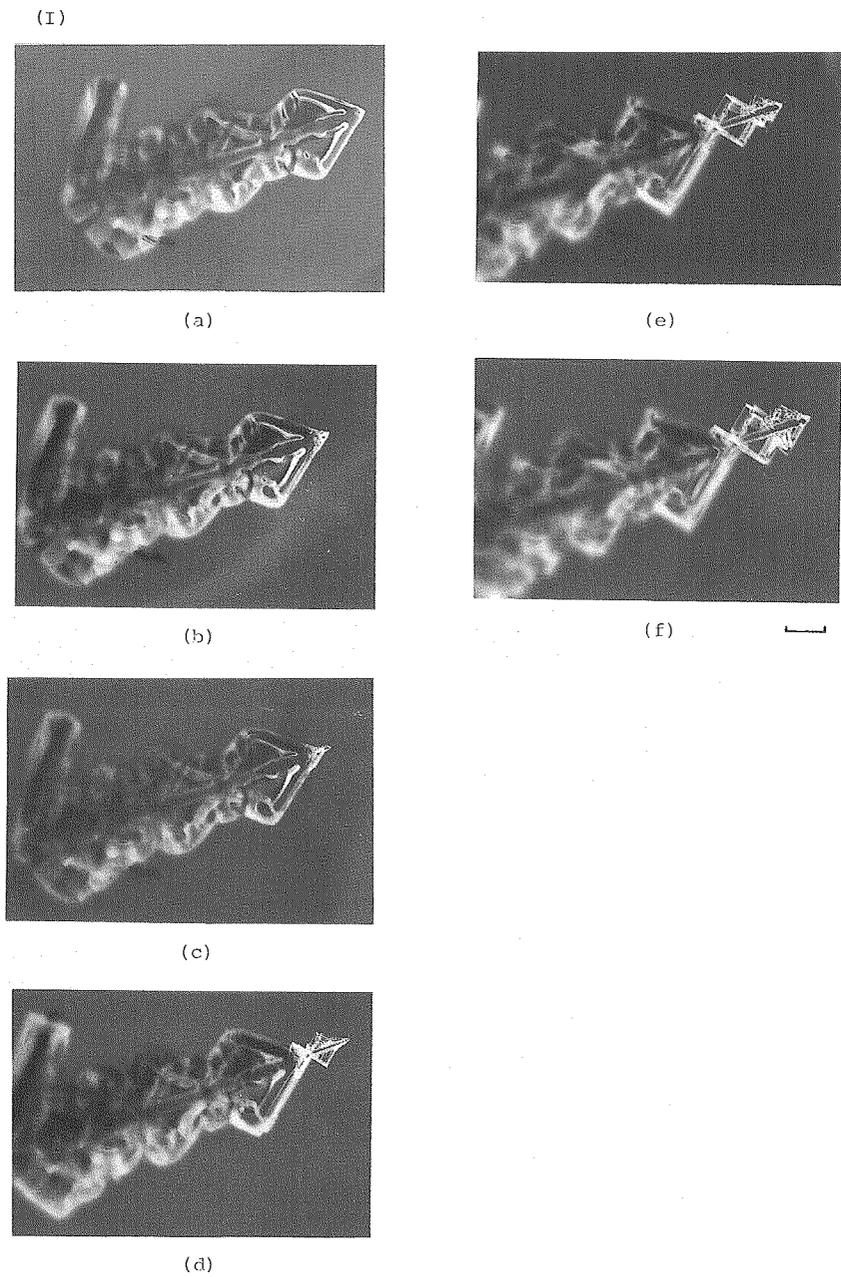
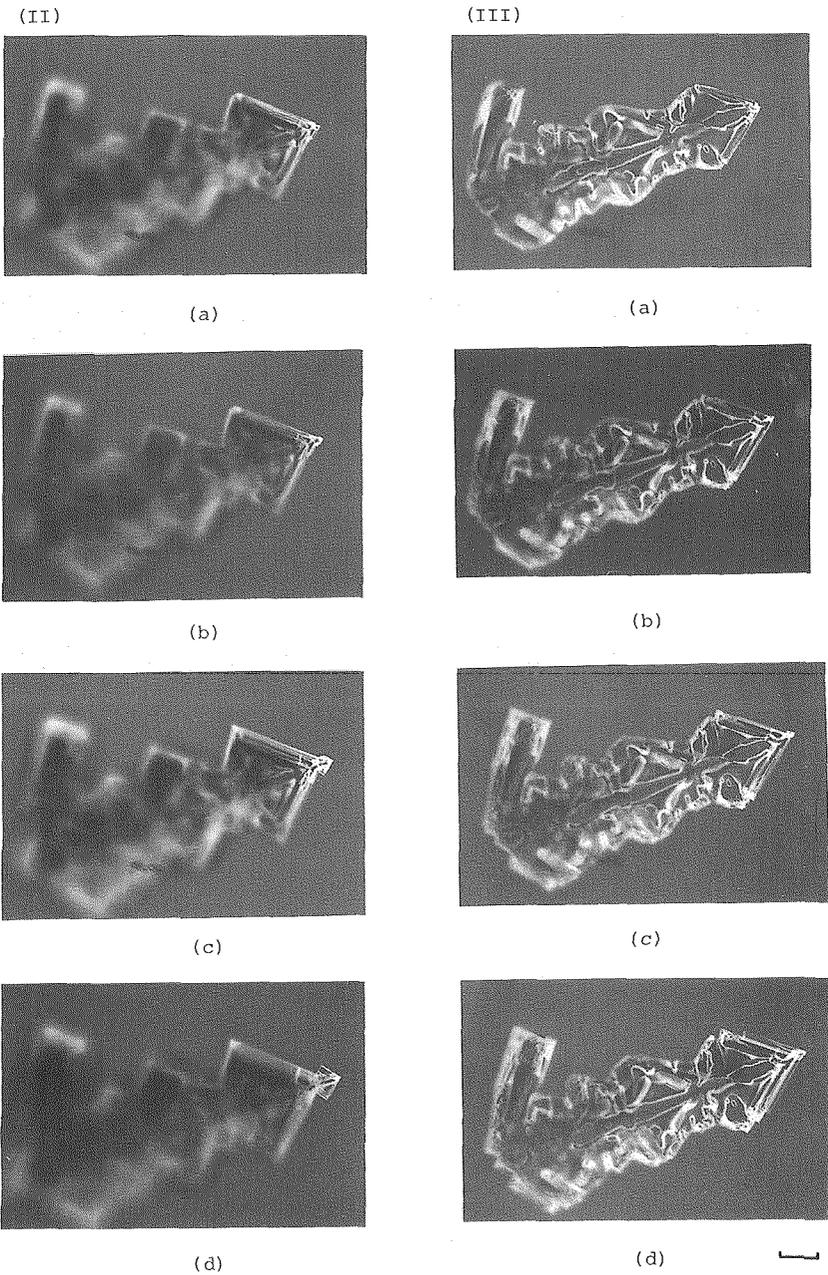
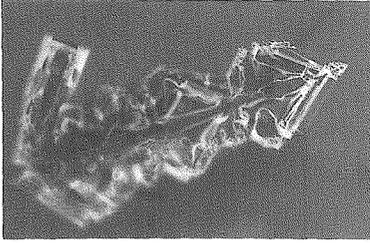
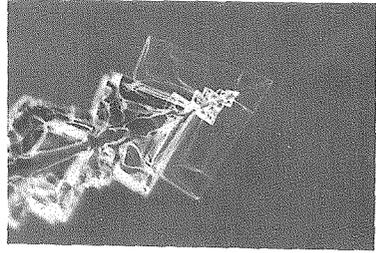


Fig. 8 Successive microphotographs of the growth stages of gohei twins.

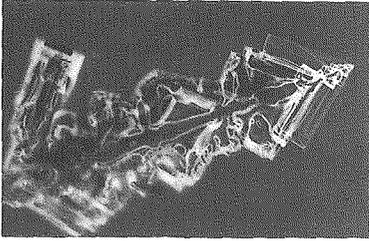




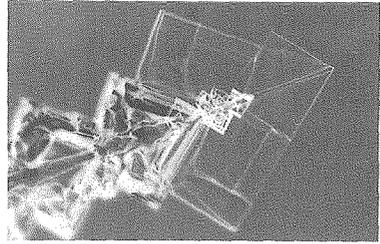
(e)



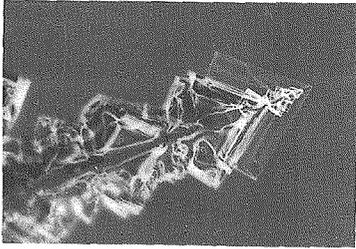
(i)



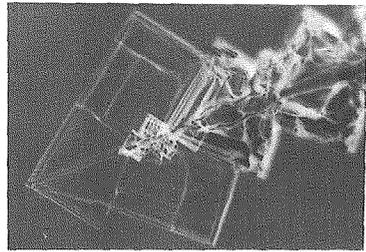
(f)



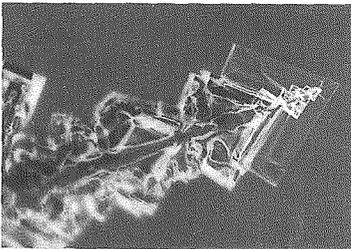
(j)



(g)



(k)



(h)



Fig. 8 (Continued)

the morning on January 14, 1986. This crystal was one with the tip angle of 78° in the gohei twins (Kikuchi and Sato, 1984). Sublimation condensation (growth) and evaporation experiments to this crystal were repeated three times. Every series were carried out at the $T_b = -30^\circ\text{C}$ in the growth temperature. The temperature difference, ΔT , was 7°C in series (I), 4°C in series (II) and 2.5°C in series (III), respectively, as indicated in Fig. 8.

The growth features at the tip of gohei twins were linearly extended prism planes of single crystals in the series (I) and (II). The direction of their principal axis (*c*-axis) was the same as the *c*-axis of the right hand side, namely, the lower half in this figure, of gohei twins. The growth features at the tip of gohei twins in the series (III) were the same twins (polycrystalline extended prism planes). The thickness of these extended prism planes was very thin as shown in the series (III)-(d) and the area was large because of small supersaturation, namely, the small temperature difference. The shape of tip after the evaporation was completed showed a groove as shown in the series (III)-(a) and Fig. 9. It is important to consider that the water vapor uniformly transfers to the groove at the tip of snow crystal at the initial growth stage and fills up the groove with the

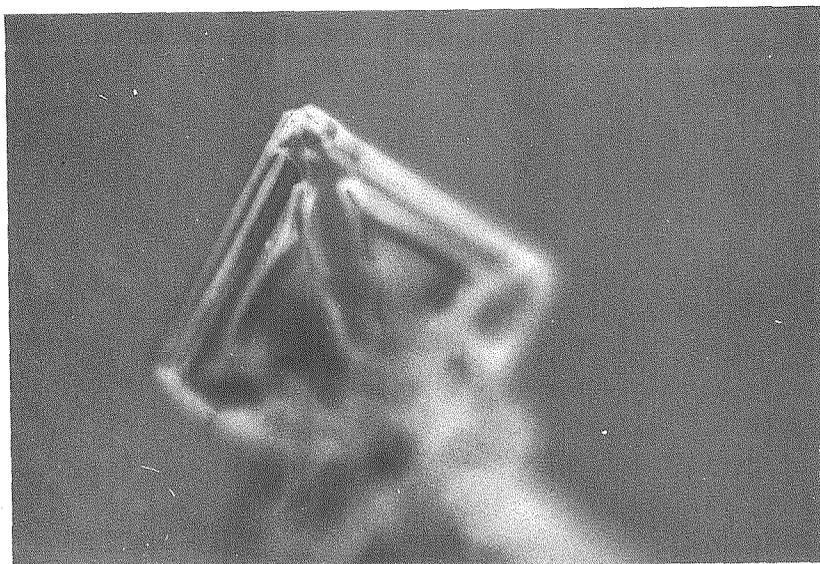


Fig. 9 A microphotograph of the shape of tip of gohei twins.

water molecules as twins. If the water vapor transfer was uniform, the gohei twins will continue to grow in twins. Therefore, it is considered that the condition of low supersaturation is suitable for the uniform water vapor transfer. Thus, it is not important to the growth of gohei twins whether the supersaturation (ΔT) is small or not. In fact, the gohei twins grew faster than the growth rate of this experiment and the thickness of prism planes was thicker.

Regarding the structure of gohei twins, a certain small angle between one prism plane and another prism plane of the gohei twins has been assumed to explain the formation mechanism of gohei twin crystals (Sato and Kikuchi, 1985). Through this experiment, the small angle between both prism planes was observed as shown in Fig. 8 (III)-(i)~(k) through a polarizing microscope, namely, the prism plane of upper part of the gohei twins grew above the prism plane of lower part of the twins. Therefore, this suggested that two prism planes of gohei twins crossed each other at a small angle.

3.5 *Sea gull type snow crystals*

Spearhead type snow crystals appear to be one of the wings of the sea gull type snow crystals. On the other hand, the spearhead type crystals are considered to be a kind of gohei twins that have the tip angle of 56° (Kikuchi and Sato, 1988). Eight growth and evaporation experiments in total were made in situ regarding the sea gull type crystals. Experimental conditions are summarized in Table 1. The temperature conditions of T_b were between -20°C and -35°C . Supersaturation conditions, ΔT , were from 1.5°C to 8°C . The eighth experiment was made by adhering the crystal on the fiber extending horizontally in space. Thus, the supersaturation condition of $\Delta T=10^\circ\text{C}$ was less than that of $\Delta T=10^\circ\text{C}$ made on the cover glasses. Temperature profiles are shown in Fig. 10 when the sea gull type crystals were observed at Inuvik. The symbols shown in this figure are the same as those in Fig. 1. It was estimated that the cloud layer was between -20°C and -35°C in the conditions above ice saturation, almost water saturation. Therefore, the experimental conditions in Table 1 seem to be the formation and growth conditions of the sea gull type crystals observed in nature. A series of the growth processes in these experiments is shown in Fig. 11. The number shown in the upper parts of each photograph in Fig. 11 corresponds to the number shown in Table 1. Individual snow crystals were placed in various positions on the cover glasses except for the Case 8. As seen in the tip of individual crystals, all of them could not continue to grow in the same shapes of the sea gull type crystals. One of the reasons why the sea gull type crystals could not continue to grow in twins may be that the tips of

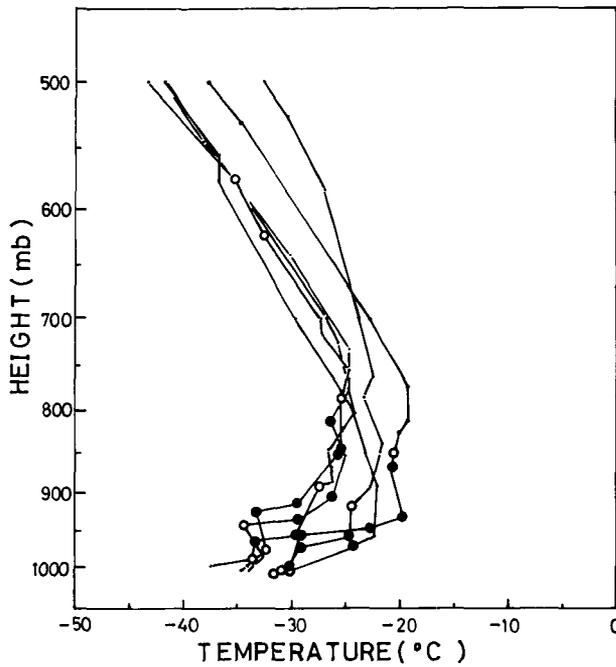


Fig. 10 Vertical temperature profiles when the sea gull type crystals were observed.

Table 1 Experimental conditions of growth of sea gull type crystals.

No.	Tb	ΔT
1	-30°C	1.5°
2	-31.5	2.5
3	-30	4
4	-30	8
5	-34	8
6	-28	8
7	-25	4
8	-20	10*

crystals were already large extended prism planes at the observation time. Another reason may be that the vapor supply around the tip of crystals was not uniform. However, the crossed plates and hollow prisms were recognized to grow at the tip of twins. They seem to give some information regarding the

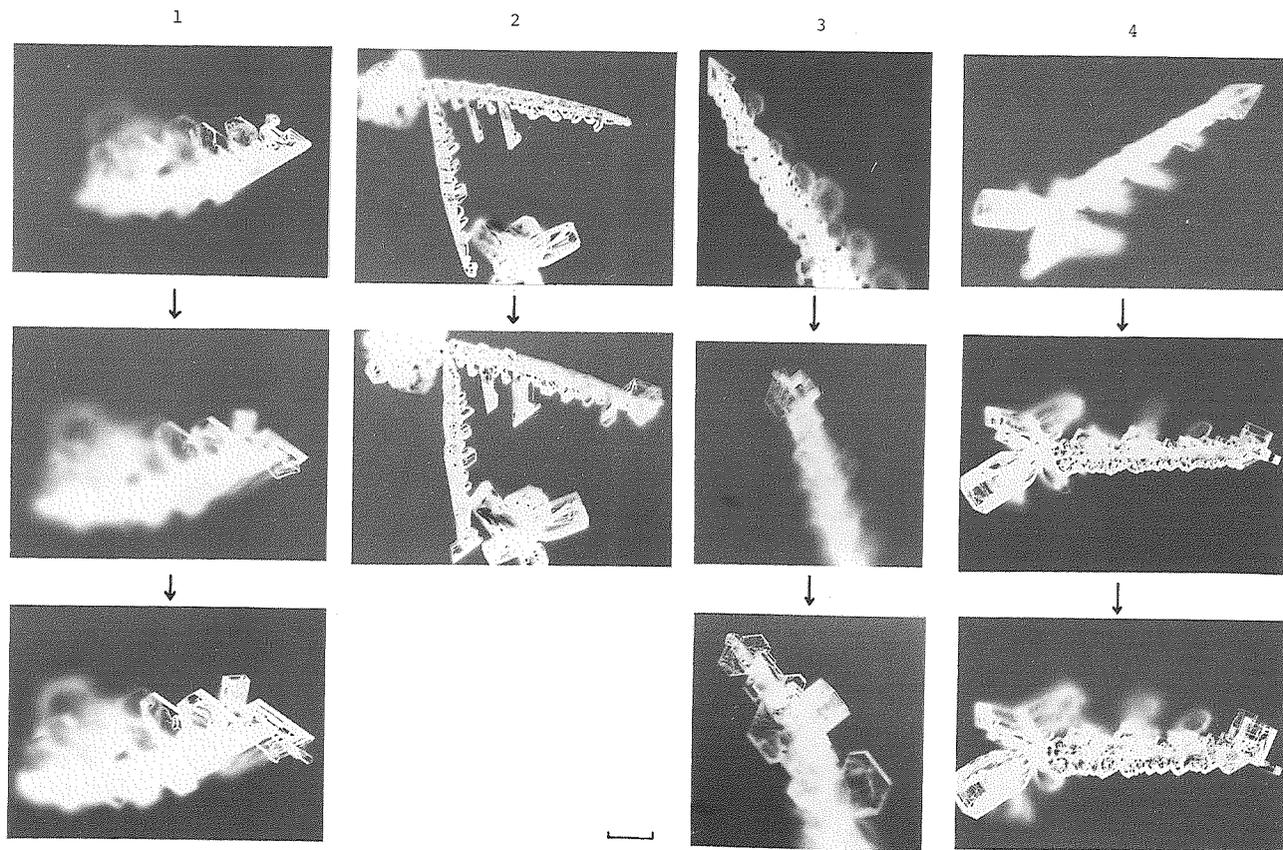


Fig. 11 Successive microphotographs of the growth stages of sea gull type crystals.

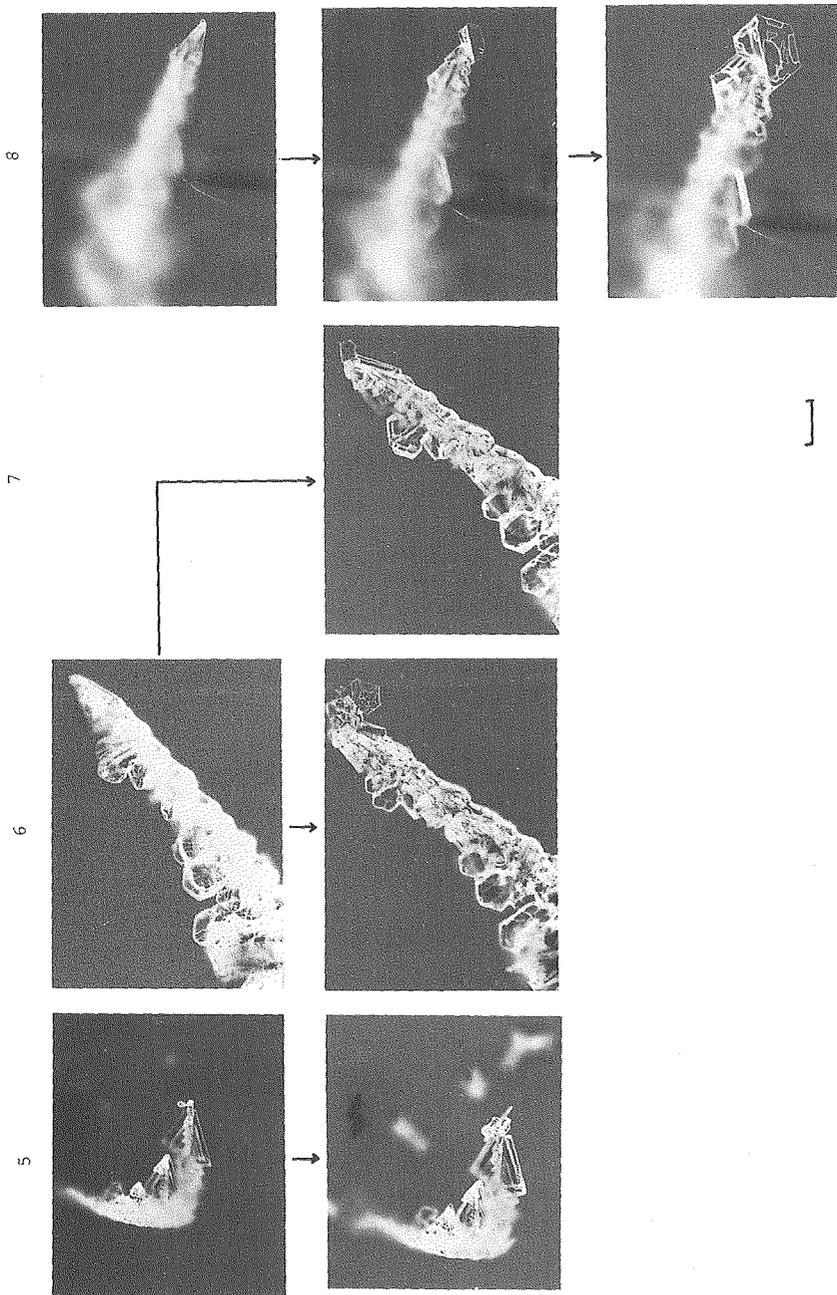


Fig. 11 (Continued)

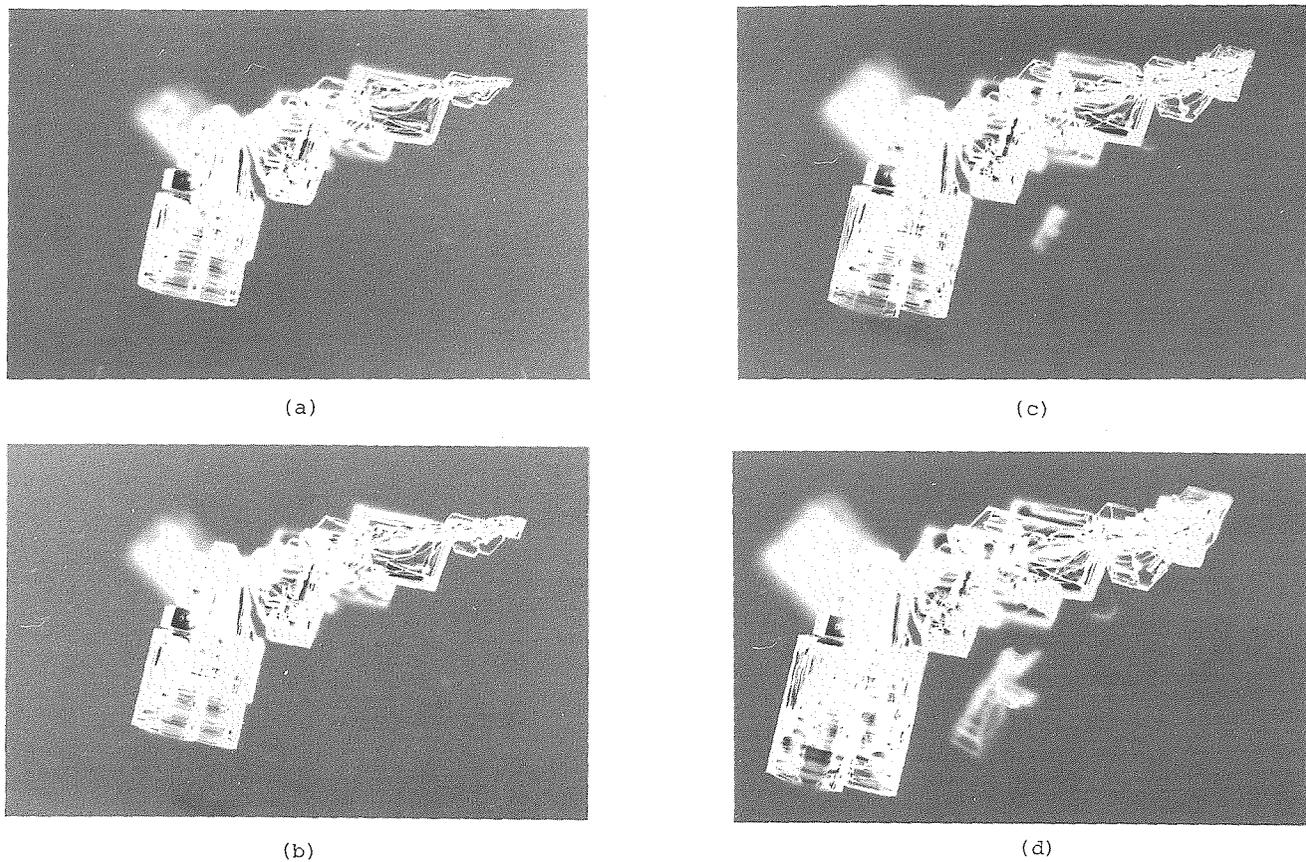


Fig. 12 Successive microphotographs of the growth stages of column and extended prism planes.

structure of the boundary of the gohei twin crystals.

3.6 Other types of peculiar shapes

Another peculiar shape of snow crystals is shown in Fig. 12. Characteristics of this crystal are that they are grown from the column and the extended prism planes repeatedly. Growth experiments were carried out under the condition of $T_b = -30^\circ\text{C}$. On the other hand, the ΔT was changed with the growth time. Increasing the $\Delta T = 1^\circ\text{C}$, 4°C , and 6°C , the crystal forms changed from (a) to (d). As seen in Fig. 12, however, the multiple extended prism planes did not appear repeatedly.

4. Concluding remarks

In situ growth experiments of snow crystals of low temperature types were carried out using a cold chamber at Inuvik in the Arctic Canada. The obtained results are summarized as follows;

- 1) When a warm air mass from the Pacific Ocean invaded into the Inuvik area, N.W.T., Canada, light rimed snow crystals were observed at the observation site. Supercooled droplets collected on snow crystals near the ground surface froze on the crystals having almost similar crystal faces. Some of them, however, showed pyramidal faces when they were grown, that is, under the conditions of a quasi-stationary state. Polycrystalline frozen droplets, on the other hand, mostly grew in crossed plates at the temperature condition of $T_b = -20^\circ\text{C}$.

- 2) Crossed plates type crystals which are one of the most typical shapes growing below -20°C , were studied under the conditions of different growth rates. As a result, it was clarified that the increasing of the growth rate was accompanied by the increasing of ΔT . The successive formation and growth of small plates which was one of the typical characteristics of the crossed plates was not observed under the condition of high supersaturations.

- 3) In situ growth experiments of the gohei twin crystals, such as gohei twins, sea gull, and spearhead were carried out using a cold chamber. The water vapor supply to the tip of crystalline boundary was considered to be very important for the continuation of growing of the twins.

- 4) The gohei twins (tip angle 78° type) was clarified to have a certain angle between two extending prism planes. Other types of gohei twins (tip angle 54° type) showed several shapes at the tip of crystalline boundary which provided the information about the structure near boundary of the twins.

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