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Investigation on the Growth and Distribution of Natural Snow Crystals by the Use of Observation Points Distributed Vertically, III

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1. Introduction

It was shown in the previous papers[1),2)] that Dr. Nakaya's *Ta–s* diagram[3)] represents fairly well the temperature conditions *Ta* of snow crystal growth of various types. Regarding the humidity conditions *s*, however, several problems were left, not being resolved. The most important was the phenomenon that snow crystals seemed to fall from not saturated cloud layers, particularly, beautiful dendritic crystals seemed to grow even in non-saturated air layers even with respect to ice surface. In this case, there were no clouds detected.

One of the possible explanations for this problem is perhaps to be gained from observing the ascending path of raido sonde balloons, because sometimes the balloons were considered to go up between clouds. However, since the humidity and temperature measurements below altitude 1000 m were carried out by Assmann's aspiration psychrometers near surface, all the factors to explain the problem are not attributable to the flying path of the balloons. The other possible explanation may be in the accuracy of the humidity measurements. It is known that exact measurement by a wet and dry bulb thermometer such as Assmann's psychrometer is difficult in cold temperature owing to the freezing phenomenon of the wet bulb. But it is sure that air is not saturated with respect to ice surface when the temperature of the wet bulb is lower than that of the dry bulb. As for the problem whether air is saturated or not saturated, therefore, the data obtained by the Assmann's aspiration psychrometer are reliable. In the results measured by GOLD and POWER[4)], GRUNOW[5)] and MURAI[6)] also, such a strange phenomenon with respect to the humidity is recognized, but these researcher were not greatly

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troubled by it, because their humidity measurements were not accurate.

In the observation of the third season, almost all efforts were pointed toward obtaining accurate data of humidity as much as possible and to clarify the problem in the growth of natural snow crystals.

2. Methods improved

The observation methods were almost the same as those in the previous season except the increase in height of shelters from the surface of snow cover and the determination of cloud top and base by the use of aircraft observation.

2.1 *Determination of cloud top and base by aircraft observation*

In the previous observations, natural snow crystals came down usually from the windward direction and radio sonde balloons went up to the leeward. Therefore, it was possible that the data obtained by the radio sonde did not

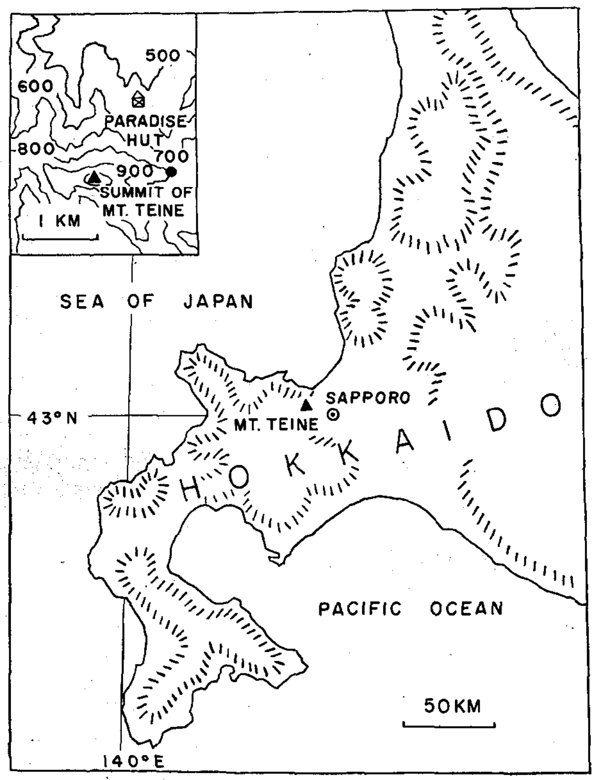


Fig. 1. Location of Mt. Teine Observation area.

always exactly represent the air condition of the air layer in which the snow crystals developed. This situation made it difficult to determine whether a cloud existed or not to the windward of the observation area. In order to confirm the existence of cloud, measurements of cloud conditions by means of aircraft were made at around 1300 everyday in the present work. The heights of cloud top and base over the observation area were determined by the altimeter of the aircraft. Pictures of clouds were also taken from the aircraft.

2.2 *Height of shelters above the surface of snow cover*

Three surface observation points named Summit (1023 m), 800 m (800 m) and Paradise Hut (560 m) were set in order to measure the temperature and humidity of free air at the corresponding altitudes as shown in the left upper portion of Fig. 1. It was feared that the surface of the snow cover exerts some influence upon the measurement of free air. Therefore, the height of shelters which housed self-recording apparatus was increased to the height of 3 m above the surface, enough to avoid any influence of the snow cover. The measure-

Table 1. Data-gathering organization.

Observation points	Altitudes	Items of observation	Observers
		Chief	Choji Magono
Summit	1023 m	Temperature, humidity Replicas of snow crystals	Tadashi Kimura
		Microscopic photograph	Katsuhiro Kikuchi
		Humidity measurement by heating dew point method	Kazuhiko Itagaki
		Charge on snow crystals	Keitaro Orikasa
800 m	800 m	Temperature, humidity Replicas of snow crystals Microscopic photograph	Ken-ichi Sakurai Reiji Ohata Tsutomu Nakamura Ken-ichi Sakurai
Paradise Hut	560 m	Temperature, humidity Replicas of snow crystals Microscopic photograph	Seiu Lee Kenji Ishizaki Tsutomu Takahashi
Mt. Teine region	1000 m	Observation from aircraft	Keiji Higuchi North Army Aviation Force of Japan
Sapporo	30 m	Rawin sonde sounding	Sapporo Meteorological Observatory

ment by Assmann's psychrometer was of course made at the same height in free air outside of the shelters.

The location of the observation area is shown in Fig. 1. The data-gathering organization is recorded below in Table 1.

3. General view of the results

In the previous observations, snow crystals of relatively cold temperature types[3] were observed. In order to observe snow crystals of relatively warm temperature types, the present observation was made in a period of not very low temperatures, *e.g.* in December (1960) during which hitherto rimed snow crystals were often observed. But unfortunately in the observation period of

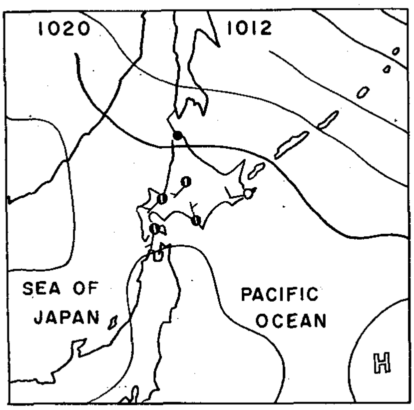


Fig. 2. 0900 15 Dec., 1960.

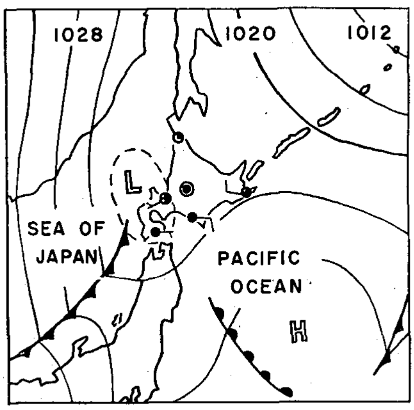


Fig. 3. 2100 17 Dec., 1960.

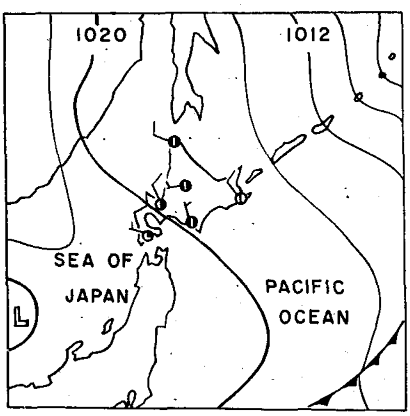


Fig. 4. 0900 20 Dec., 1960.

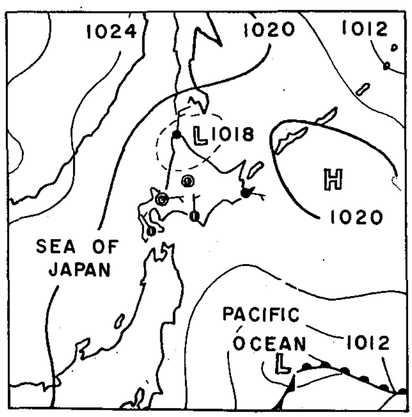


Fig. 5. 0900 21 Dec., 1960.

this year, no warm front with accompanying dense warm clouds past over the observation area. Therefore only light snow falls occurred from thin clouds owing to the westerly monsoon, although local heavy snow showers were observed near by at Iwamizawa which is located only 18 miles to the east of the observation area. This marked contrast in snow fall is considered to be due to direction of upper layer wind. The point will be discussed in the future.

The surface weather maps in the observation period are shown in Figs. 2–5. In the figures one sees that the width between isobars around Hokkaido Island was large, in other words, the climate was calm, and most of the clouds over the area were of stratiform as shown in Pls. I–III. In the observation period, only one weak cold front passed over the observation area.

Almost always during the period, it was snowy in the observation area, even when it was fine at Sapporo which is located near. This phenomenon is understood by considering that the Mt. Teine region was always covered by snowy clouds owing to orographic ascending air as seen in Pl. I. This may be more clearly understood if one considers clouds over Sapporo City as to be dissipated by orographic decending air from the mountain region.

3.1 *Types of snow crystals and aerological conditions*

The results obtained in the period of the present observation are collated in Fig. 6. Types of snow crystals observed are shown in the upper half part of the figure. The first, second and third horizontal columns of the part represent the types of the snow crystals observed at Summit, 800 m and Paradise Hut observation points respectively. The type in the highest line of each column means that snow crystals of that type were most frequently observed for the observation period of two hours from one hour before to one hour after a radio sonde sounding time. The explanation of the symbols for types of snow crystals is given in Table 2.

The lower part of Fig. 6 represents the time cross-section in which the coordinate shows the altitudes above sea level in meters, solid lines are isotherms, dotted lines are equal relative humidity with respect to ice surface, and shaded areas are moist regions of humidity higher than ice saturation. The height of cloud top and base is indicated by the symbols shown in Table 3. Everyday the top and base of cloud to the windwards was measured by an aircraft at 1500. The height of cloud base at the times other than 1500 was determined by visual method or cloud photographs taken from Sapporo.

Table 2. Symbols for snow crystal types.

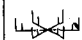
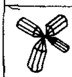
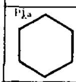
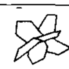
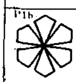
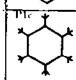
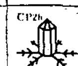
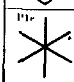
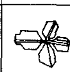
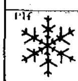
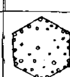
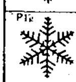
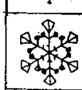
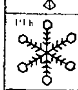
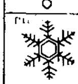
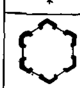
	Hollow hexagonal column		Stellar crystal with scrolls or thick plates
	Thick plate of skelton form		Stellar crystal with needles or sheaths
	Combination of columns		Stellar crystal with spacial plate
	Hollow bullet		Stellar crystal with spacial dendritic branches
	Combination of bullets		Plane with rimed spacial branches
	Simple plate		Radiating type of dendritic plane
	Small hexagonal plate		Radiating type of plate or sector
	Branches in sector form		Column with plates
	Plate with simple extension		Bullet with plates
	Broad branches		Bullet with dendritic crystals
	Simple stellar form		Radiating type of columns and plates
	Stellar germ		Irregular assemblage of columns and plates
	Ordinary dendritic form		Rimed plate or sector
	Fernlike crystal		Graupel-like crystal with not rimed extensions
	Dendritic crystal with sectorlike ends		Lump graupel
	Stellar crystal with plate at ends		Broken branch
	Plate with dendritic extension		Rimed broken branch
	Plate with scrolls of thick plates		

Table 3. Code indications for cloud top and base determined by surface and aircraft observations.

	Cloud top	Determined by aircraft observation
	Cloud base	
		Determined by surface observation

3.2 *Day to day account*

15 Dec. 1960. In the time cross-section one sees there was no moist air layer in the daytime of 15 Dec. However the top and base of clouds were observed as seen in the time cross-section. Photo. 3 of Pl. II shows the clouds to the west of Mt. Teine. On the other hand, considerable snow crystals of various types were observed as seen in Fig. 6. Those facts mean that clouds actually existed around the summit of Mt. Teine and the snow crystals fell from the clouds or flew from the clouds to the windwards.

If some clouds existed in the layer between altitudes 1000 and 2000 m, the temperatures of the layers are considered to be –12.5 and –17.5°C. Snow crystals are expected to develop to dendritic type in the temperature range between –12.5 and –17.5°C.[3] Actually, most of the crystals observed on this day were of dendritic type as expected. It is noted that graupels and rimed crystals were observed for a short period before noon of this day. But no clues to suggest the mechanism of growth of the graupels were obtained from only this datum of such a large scale.

16 Dec. On 16 Dec. also, there was little moist atmosphere as seen from the time cross-section, but considerable snow crystals of various types including graupel were observed. The climate was fairly calm on both 15 and 16 as would be supposed from the slow pressure gradient in Fig. 2. Those pressure patterns as seen in Fig. 2 were representative in the observation period when monsoon was prevailing in the observation area.

It is noted that snow crystals of spacial type were fairly often observed, for examples, stellar crystals with spacial dendritic branches and stellar crystal with rimed spacial branches. The snow crystals of spacial types are considered to be formed when temperature inversion[7] exists around air layer zone corresponding with temperature range from –15 to –20°C. Actually in Fig. 6 one may see that fairly large temperature inversion existed in the zone between −15 and −17.5°C isotherms.

17 Dec. In the later half of this day, a cold front passed over the observation area as seen in Fig. 3 and there came to exist a dense and thick moist air region after the noon as shown in Fig. 6. Pictures taken at 1530 (Photo.5) show that there were lower clouds of thin stratiform and also upper layer clouds. It is considered that the space between the two cloud layers was gradually filled up with moist air after the evening and that the top of the moist air region reached the air layer of temperature −35°C and of altitude 4500 m. The upper half of the moist region was highly supersaturated.* In accord with existence of the moist region, snow crystals of cold temperature types were predominant as seen in Fig. 6, for example, irregular assemblege of columns and plates (−25∼−35°C), combination of bullets (−25∼−40°C). Since the moist region ranged in temperature from cold to relatively warm, snow crystals of mediate temperature types were also observed, for example, hollow hexagonal column (−20∼−30°C), radiating type of columns and plates (−20∼−25°C) and of plate or sector (−10∼−13°C), and crystals of plane types (−13∼−18°C).

18 Dec. At 1500 of this day, it may be seen that air temperature rose rapidly in contrast with the decrease in relative humidity at layers higher than 2100 m and that a strong temperature inversion occurred. The inversion is considered to have resulted from the descending of upper air layer. Snow crystals of almost all types excepting cold temperature types were observed at this time. Particularly it was noted that snow crystals of capped column types were included in the snow crystals observed. This fact tells us that there existed fairly moist air contained in both the air layer of temperature −20∼−25°C near the cloud top and in the air layers of −12.5∼−17.5° C near the cloud base.

19 Dec. There were no moist layers before noon of this day, but snowy cloud of nimbostratus was seen over Mt. Teine as shown in Photo. 4, Pl. II; various snow crystals of low vapour supply types were observed as seen in Fig. 6. The edge of the clouds shown in Photo. 6 perhaps did not reach the place above the radio sounding station. The clouds are considered to be dilute in cloud droplet concentration although the clouds were thick vertically, because the snow crystals observed were of low vapour supply types. The temperature conditions of the moist layers ranged from cold to fairly warm.

* The grade of the supersaturation was high, but its absolute value was not high, because the temperature was low.

After noon, the clouds got thicker and denser. Corresponding to the development of the dense clouds, snow crystals of ample vapour supply types, for example, dendritic crystals, fern-like crystals began to occur as seen in Fig. 6. Around midnight, highly developed dense clouds passed over the observation region, but no observation of crystal types was made.

20 Dec. Through the day, a moist air zone at from 900 to 2000 m and inversion zones from 1800 to 2500 m existed above the observation area as seen in the time cross-section. Photo. 6, Pl. III shows a side view of clouds of stratiform at 1530. In the photograph one sees that snow fall has begun to form just under the cloud top where the cloud was not yet glaciated. On the other hand, almost all snow crystals were of dendritic types which developed in the temperature condition between $-12.5 \sim -17.5$°C ($1000 \sim 2000$ m). This fact lets one know that the top of actual clouds did not reach the base of the inversion zone except at 1500 when the base of the inversion zone was depressed. Only at this time, 1500, were snow crystals of spacial types observed. The snow crystals of spacial types are considered[7] to develop in a temperature inversion condition around -20°C. Considering those results observed, the cloud top was considered to reach the altitude 2000 m although a depression of the top of moist region was seen at 1500.

21 Dec. The situation on 21 Dec. was similar to that on the previous day excepting the existence of higher cloud in the morning hours. Since snow crystals from a temperature region colder than -22.5°C were not observed, it is considered that this cloud of higher layer made no contribution to the snow crystal formation. The crystal types observed were similar to those in the previous day, but it was noted that snow crystals of densely rimed types were observed after noon and at night, for example, graupels at 1500 and rimed spacial dendrites at 2100.

Regarding the rimed crystals, it was noted that the lapse rate of temperature below altitude 3000 m was much larger than that of the previous day, in other words, lower layers of 21 Dec. were unstable compared with those of 20 Dec. The conditions under which graupel fall will be discussed below in detail.

4. Cloud conditions in which the graupel developes

Five vertical profiles of temperature and humidity accompanied by graupel fall were obtained by radio sonde sounding during the observation period. Comparing the profiles with those without graupel fall, it seems that when graupel fell the lapse rate of the lower layer was fairly large. Those lapse rates are shown in Table 4 in which the upper lines show the lapse rate,

Table 4. Lapse rates during graupel-fall and snowfall.

Dates	Lapse rates (500–3000 m) °C/km	Existence of inversion below altitude 3000 m	Precipitations	Types of clouds
0900,15 Dec.	6.9	no	Snow & graupel	
2100,16	6.5	yes	〃	
1500,17	7.9	no	〃	As, St
0900,18	7.8	no	〃	Sc
1500,21	6.5	no	〃	St
	mean 7.1			
1500,15	6.5	yes	Snow	Cu
2100,15	3.9	yes	no	fine
0900,16	5.5	yes	Snow	
1500,16	5.3	yes	〃	St
0900,17	5.4	yes	〃	St
2100,17	7.2	no	〃	
1500,18	5.1	yes	〃	Sc
2100,18	6.4	no	〃	Highly developed clouds
0900,19	6.5	no	〃	Sc
1500,19	5.1	no	〃	St
2100,19	6.1	no	〃	Highly developed clouds
0900,20	4.7	yes	〃	St
1500,20	4.8	yes	〃	St
2100,20	3.8	yes	〃	
0900,21	6.0	no	〃	Highly developed clouds
2100,21	5.5	no	〃	
	mean 5.0			

existence of inversion and cloud type during snowfall accompanying with graupel, and the lower lines show the conditions accompanying snowfall only. In the table one may see that the lapse rate during snowfall accompanying graupel (mean 7.1°C/km) is about the same as the wet adiabatic lapse rate (7.5°C/km) in the observation period, but is much larger than the lapse rate during snowfall only. Another fact to be marked during graupel fall was that temperature inversion did not exist below altitude 3000 m except at 2100, 16 Dec. On the other hand, during the period without graupel fall, temperature inversions existed in almost all cases except in the case of highly developed cloud. It was expected that graupel developed in strong ascending air current which usually accompanies highly developed cumulus clouds. But actual graupels were observed when fairly low cloud existed.

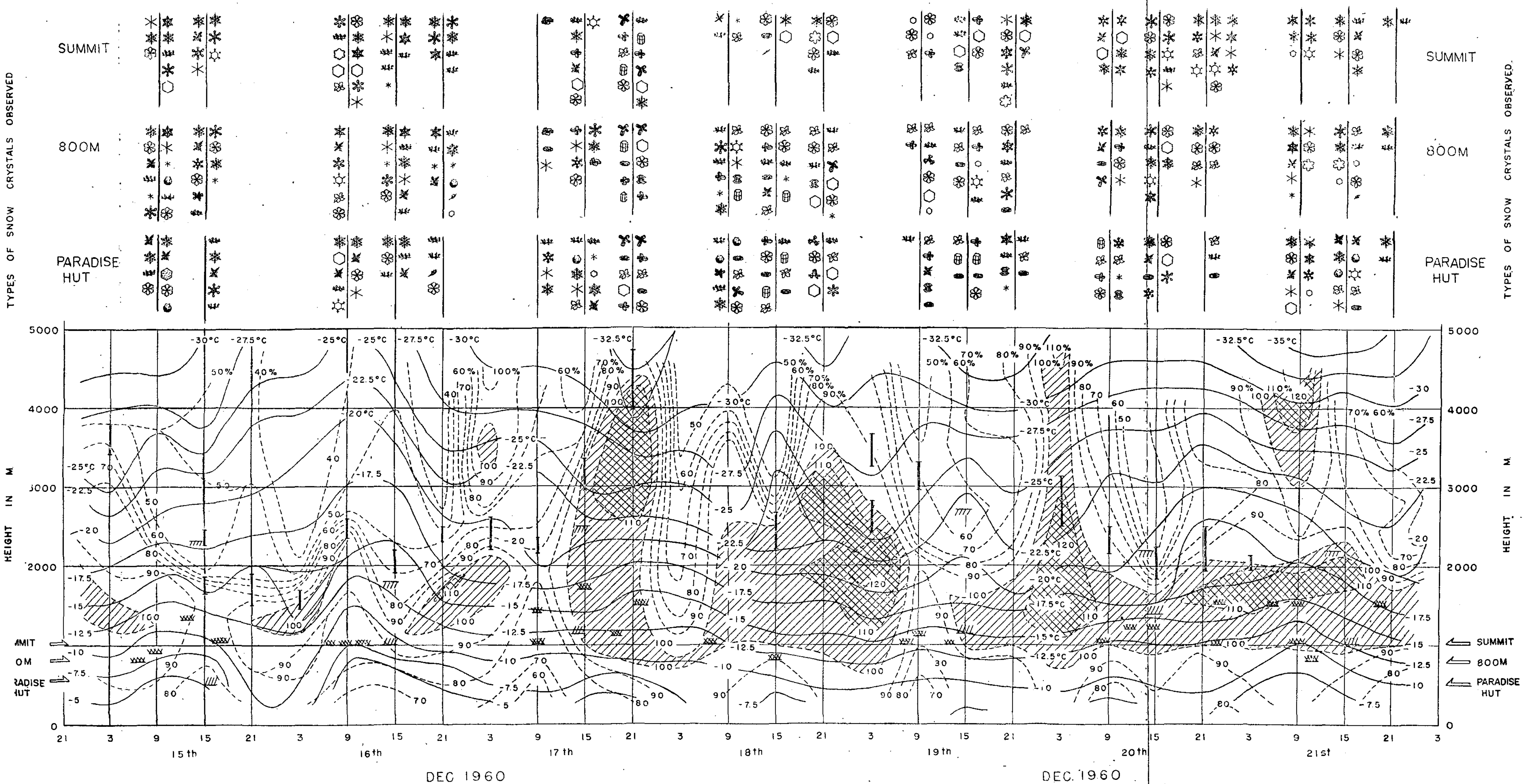


Fig. 6 Types of snow crystals observed and time cross-section during the observation period.

From highly developed clouds, only snow crystals fell, for example, at 2100 on 18, 2100 on 19 and 2100 on the 21st. The type of those highly developed clouds was not determined exactly, because these things happened at night. But since the types of snow crystals which were observed in the period were not of ample vapour supply types, it is supposed that the clouds were not dense.

As for the observation period, it was concluded that the graupel developed under the condition that the lower layer was not so stable as to permit inversion exist below altitude 3000 m. Under such a condition, local ascending air current would occur somewhere other than the radio sonde station and wet air would be supplied from the nearby sea surface to the bottom of the ascending air current. On the other hand, it is supposed that supercooled cloud droplets at lower level supplied from sea surface are needed for the growth of graupel but that the existence of highly developed cloud is not always needed.

5. Ice fragments in air at the summit of Mt. Teine

The size distribution of cloud particles was observed at the summit of Mt. Teine during the observation period by the use of impactor method. Sometimes ice fragments were observed together with cloud particles. Therefore, observation by the use of impactor was made even when cloud was not visible at the summit. Ice fragments obtained in this case are shown in Pl. IV. The possibility that some fraction of the ice fragments observed were produced when snow crystals were introduced into the impactor and were impacted on the oil covered glass plate is considered, but the fraction of fragments produced in this way is not supposed to be large, because often no ice fragments were observed even during snowfall. It is supposed therefore that most of the fragments observed were suspended in the free air originally. The size of the ice fragments ranged from 10μ to 300μ and the concentration of the fragments was of the order $1\,cc^{-1}$. This value of concentration is small compared with the usual concentration of condensation nuclei, but it is larger than that of natural freezing nuclei. The size of the ice fragments is fairly large as freezing nuclei, but they can act as freezing nuclei because they are ice itself. Therefore the existence of the ice fragments may play an important role in the glaciation of supercooled clouds during winter season, if such freezing nuclei are supplied by chain reaction mechanism of falling snow crystals. Considering the existence of the ice fragments, it is well understood that at the observation mountain area, almost always it was snowy without any continuous supply from other areas.

6. Difference between the trajectories of falling snow crystals observed and radio sonde balloon used

Monsoon from WSW direction was usually prevailing in winter season over the observation area. Specially this was the case in upper layer wind. Following is a representative example of the trajectory of snow crystals under westerly wind. Considering their falling velocity and wind speed, it is considered that fern-like snow crystals which were observed at Mt. Teine flew from about 30 km to the west, in the case of rimed crystals they came from about 15 km to the west as indicated by arrows in Fig. 7.

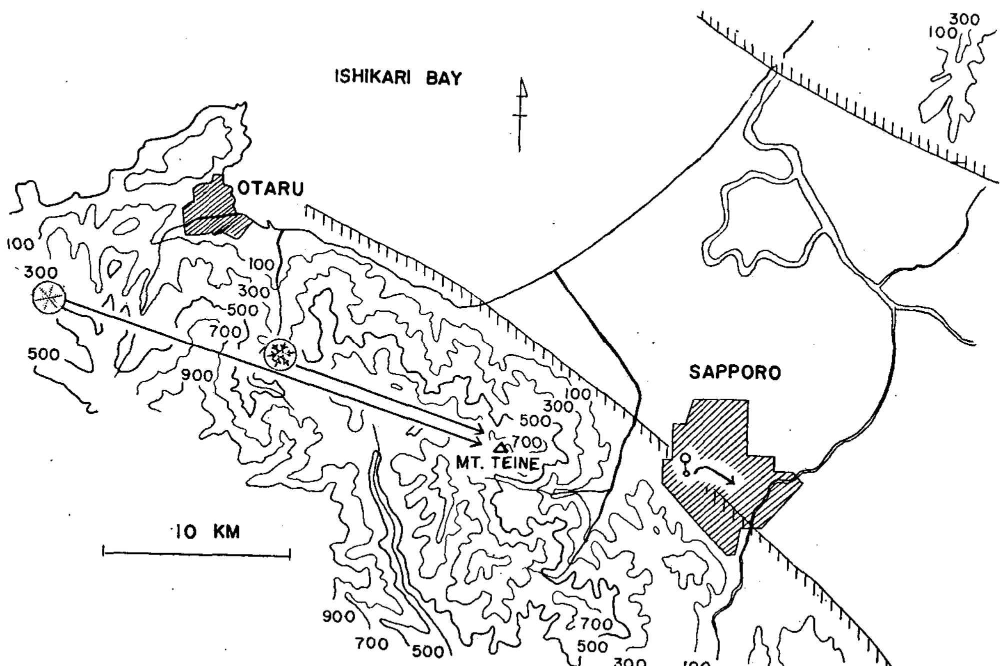


Fig. 7. Horizontal trajectories of falling snow crystals and radio sonde balloon.

On the other hand, the radio sonde balloon went up to the south east differing from the trajectory of the snow crystals as shown by the short curved arrow in the figure. The edges of the cloud region are also represented in the figure. One sees that the radio sonde balloon went out from the cloud region when it ascended and then it is that severe difficulties result from the difference between the trajectories of snow crystals and of a radio sonde balloon in analysing the condition of snow crystal growth.

In spite of such expection, the data from radio sonde represented fairly well the reasonable conditions for crystal growth as stated in both the present

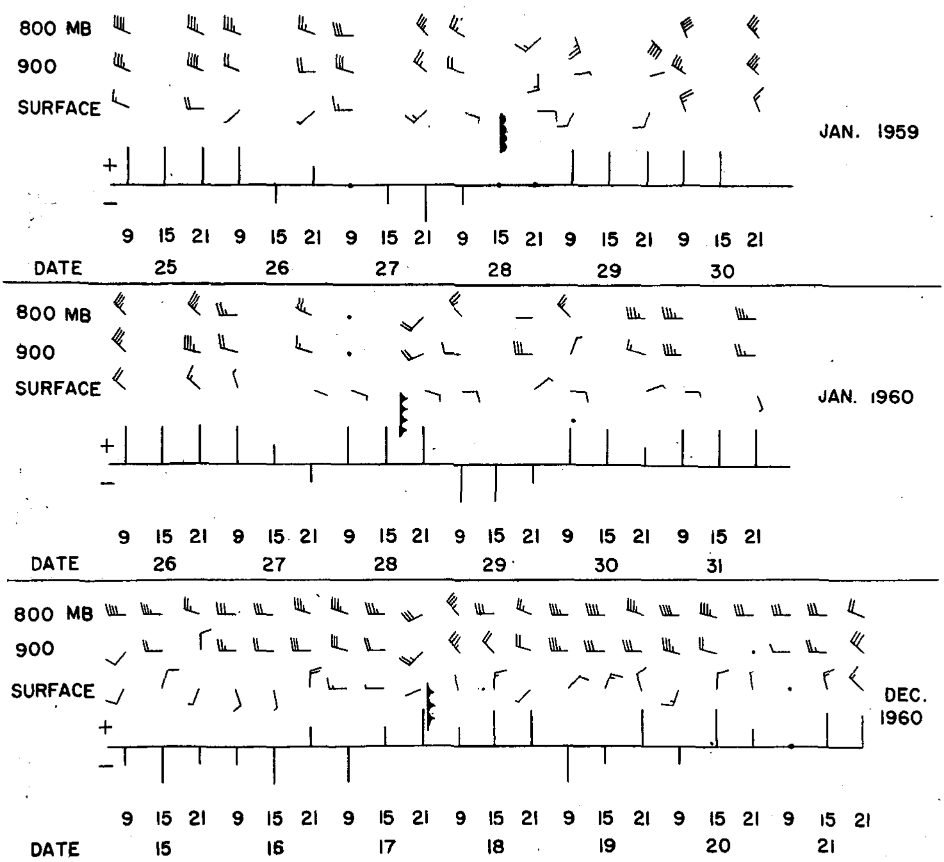


Fig. 8. Directions of surface and upper air layers winds.

paper and in the previous papers.[1),2)] To clarify the problem, the importance of the vertical distribution of upper layer wind was noted. In Fig. 8, the wind speed and direction at 800, 900 mb and surface level are plotted to dates of the three observation periods. The time of warm and cold fronts which passed over the observation area are also shown by symbols. The short vertical lines under the surface wind marks mean that the lines of positive direction represent the cases in which data from the radio sonde agreed with the condition for the crystal growth; the other lines of negative direction represent the case of disagreement between the data from radio sonde and the condition of crystal growth. The length of the lines of positive or negative directions indicates the grade of agreement of disagreement.

In Fig. 8, it is noted that when there was no wind shift between upper layer and surface, the agreement was good, for example: on 25 Jan. 1959, 30 Jan. 1959, 26 Jan. 1960, 18 Dec. 1960 and 21 Dec. 1960. But when strong wind shift existed between upper layer and surface level, disagreement was large, for example: on 27 Jan. 1959, 29 Jan. 1960, 15 Dec. 1960 and 19 Dec. 1960. The agreement and the disagreement are accounted for by considering that when a local wind of direction different from that of wind at mountain area occurs at Sapporo, the condition of lower layer at Sappro is very different from that of the mountain area. Accordingly, the data of lower layer obtained by radio sonde does not show exactly the condition of upper air layers above the observation area, although it is considered that at upper layer the meteorological condition is nearly the same as in the other place nearby. The problem will be serious even if the radio sonde station is close to the observation area. Therefore, it is concluded that in order to make a more accurate analysis of the meteorological conditions of the growth of snow crystals, other observation methods need to be used, for an example, a dropping sonde whose balloon takes its trajectory like that of the falling of snow crystals. The measurement by means of such a dropping sonde is in preparation for the comming season.

7. Conclusion

From the observations in the three seasons hitherto, the conditions under which natural snow crystals of various types developed were fairly clarified, and it is supposed that more exact results can not be expected from the method used hitherto. To carry this work farther, it is hoped that sonde may be dropped into marked clouds or that the snow crystals within the remarked clouds may be observed by means of aircraft, simultaneously with air condition.

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Pl. I Clouds over observation area.

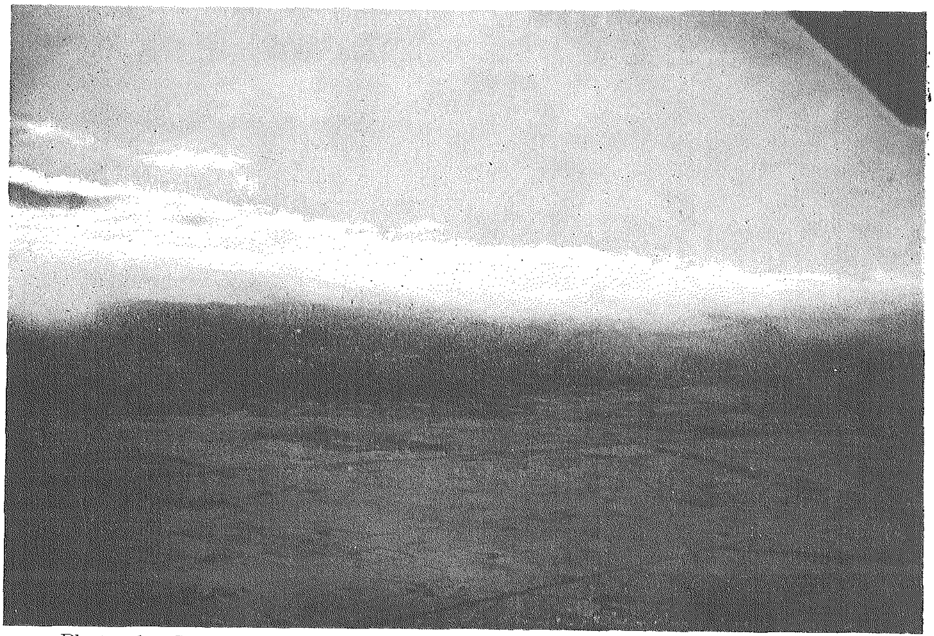

Photo. 1. Snow clouds over Mt. Teine observation area. 1530, Dec. 21, 1960.

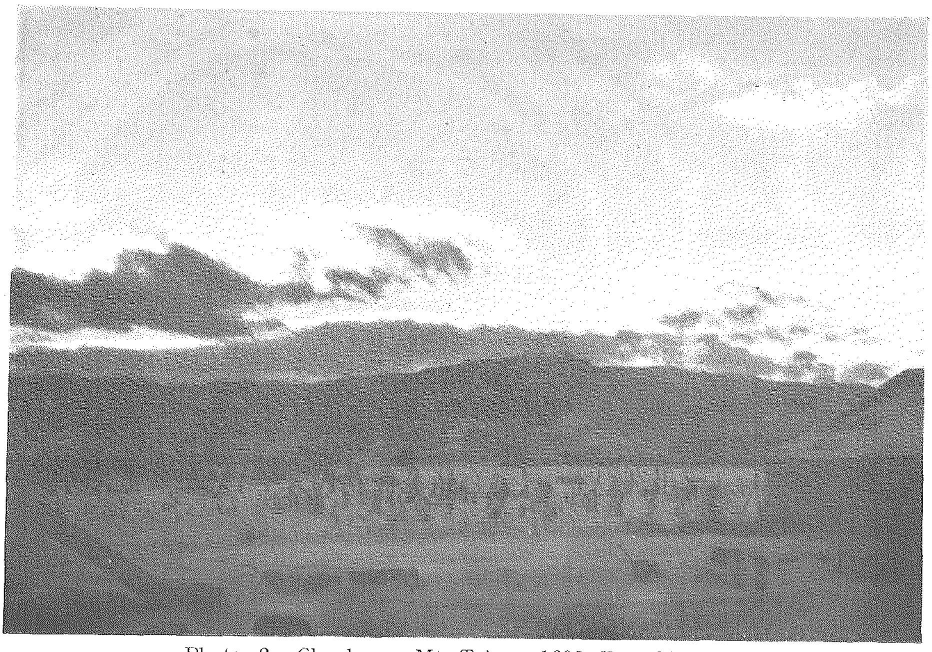

Photo. 2. Cloud over Mt. Teine. 1600, Dec. 21, 1960.

Pl. II Snow clouds over observation area.

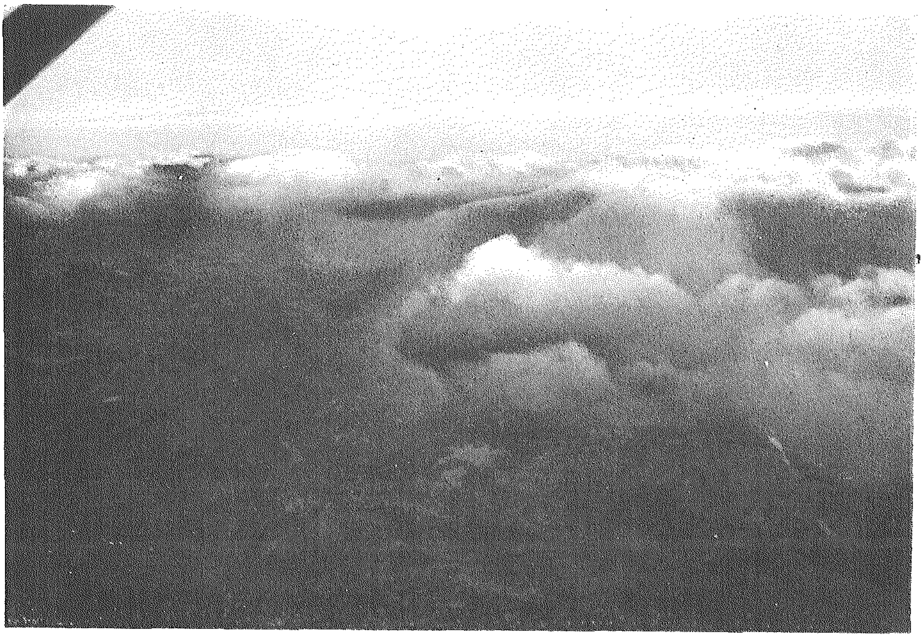

Photo. 3. Snow clouds near the top of Mt. Teine. 1530, Dec. 15, 1960.

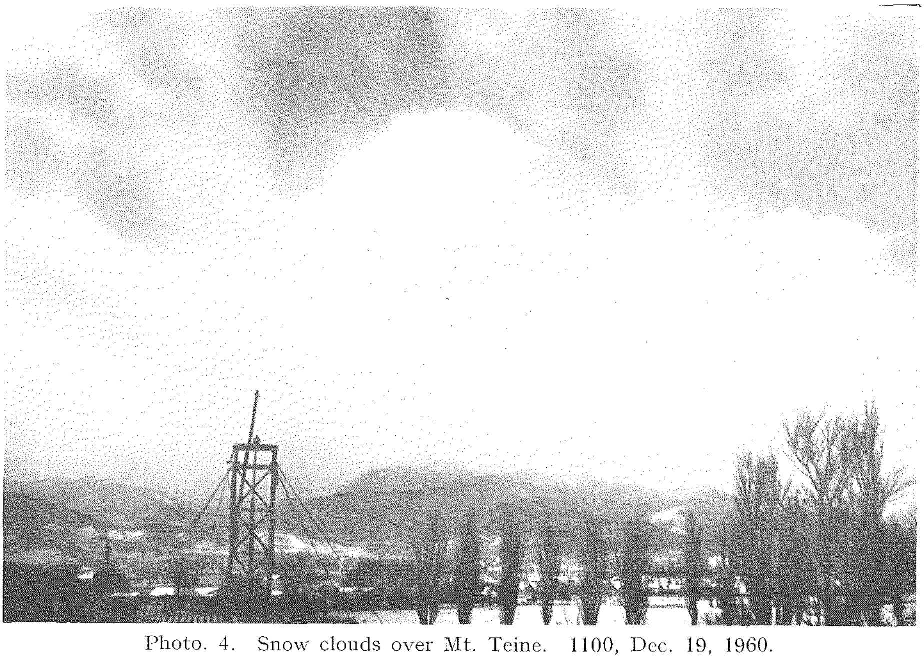

Photo. 4. Snow clouds over Mt. Teine. 1100, Dec. 19, 1960.

Pl. III Thin layer clouds over observation area.

Photo. 5. Thin layer clouds over Mt. Teine. 1530, Dec.17, 1960.

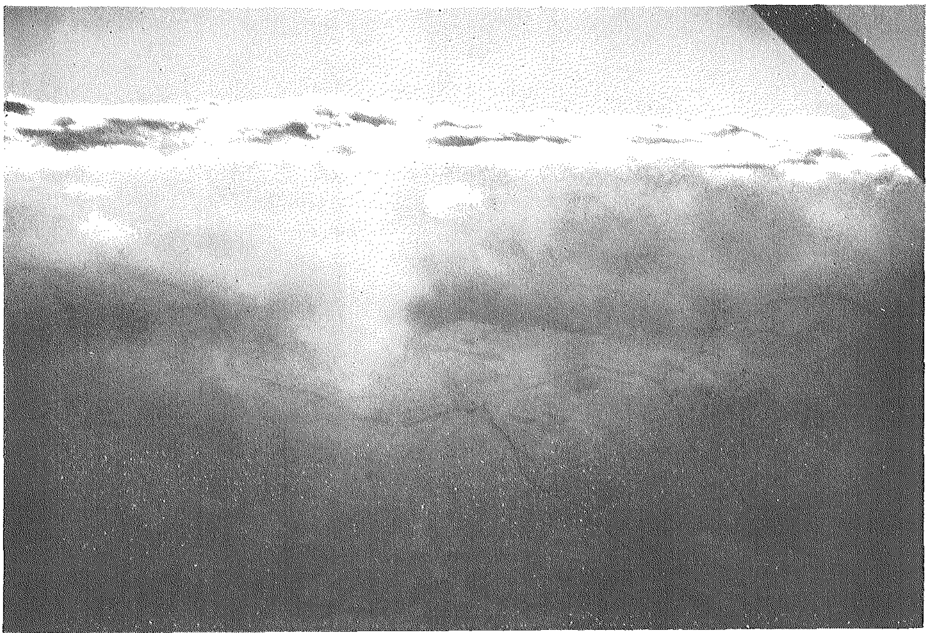

Photo. 6. A thin snow cloud over Mt. Teine. Snow fall begins from just under cloud top. 1530, Dec. 20, 1960.

Pl. IV Ice fragments in air during snowfall.

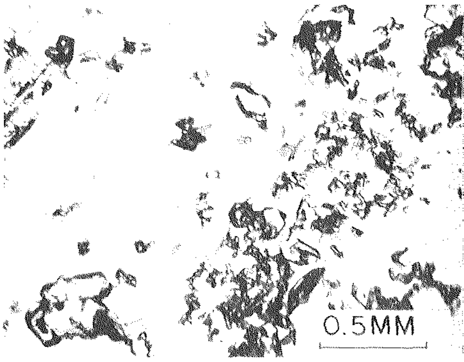

Photo. 7. 1.4/cc 2213 17 Dec., 1930.

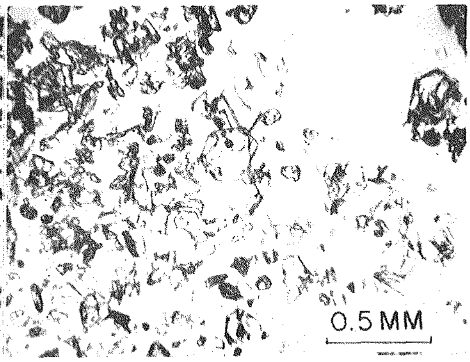

Photo. 8. 2.6/cc 2250 17 Dec., 1960.

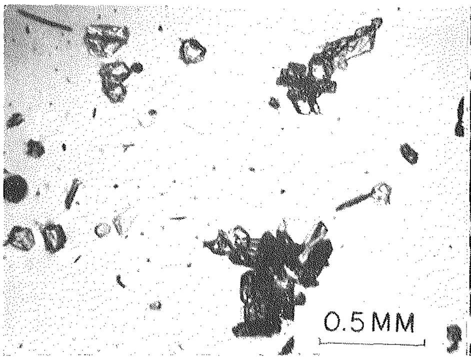

Photo. 9. 1.8/cc 2205 18 Dec., 1960.

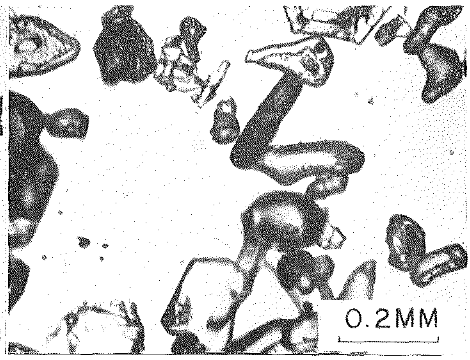

Photo. 10. 1/cc 0805 19 Dec., 1960.

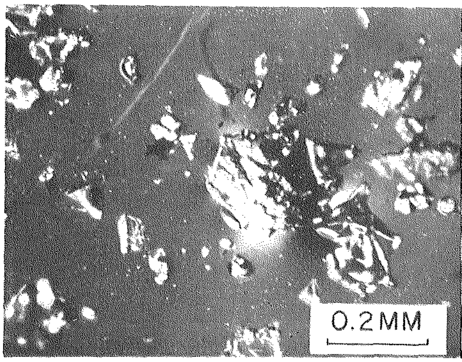

Photo. 11. 2.4/cc 1436 20 Dec., 1960.

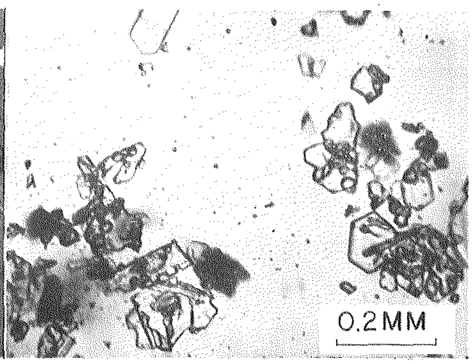

Photo. 12. 1.4/cc 1510 21 Dec., 1960.