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A Study on the Snowfall in the Winter Monsoon Season in Hokkaido with Special Reference to Low Land Snowfall

(Investigation of natural snow crystals VI)

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Abstract

An observation network was organized in the Ishikari Plain on the west coast of Hokkaido Island, and the snowfall under north-west monsoon in winter season was observed. The snowfall under such meteorological condition was of low land type in which the snowfall was heavier in low land area than in the mountain area.

From the results of the observation, it was concluded that clouds and snow crystals were formed within the cold air mass from the Siberian Continent, in other words, below the upper surface of the cold front. Thus it may be said that the formation of clouds and snow crystals had no direct relation to the ascending air currents due to cyclones, fronts or upslopes of mountains. Furthermore, because the clouds in the monsoon season were very low and consisted of band type, snowfall from the clouds frequently was localized to band type areas in the low land near the coast.

1. Introduction

It is well known that the north-westerly winter monsoon brings heavy snowfalls to the west coast of Japan. The mechanism of the snowfall has been generally explained in the following manner. When the cold and dry air mass from the Siberian Continent passes over the Japan Sea, it comes into contact with the warmer sea water and is supplied with heat and vapor from below, in such a way that it becomes an unstable air mass. When this wet and unstable air mass passes over the mountains in Japan, clouds are formed which gives rise to the heavy snowfall on the west side of the mountains.

Recently the snowfall of this type was noted by meteorologists in Japan, because sometimes it is considerably heavier in low land areas than in higher mountain areas and the low lands suffer considerable damage. We call a snowfall of this type "Satoyuki" (low land snowfall) and snowfall of the usual type "Yamayuki" (mountain snowfall). In the case of low land snowfall,

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the snowfall is heavier in low altitude areas as described above, while in the case of mountain snowfall, the snowfall is heavier in mountain areas owing to the orographic ascending air current, as may be expected.

The snowfall in the monsoon season has another property. We are referring to the fact that the snowfall is extremely localized in spite of a uniform atmospheric pressure pattern of the monsoon type, namely west-high east-low type, for instance as shown in Fig. 1. According to this property of snowfall of low land type, a detailed forecast of a snowfall is very difficult.

At the beginning a meteorological study of such snowfalls in the monsoon season was initiated by the Sapporo Meteorological Observatory[1] in the Ishikari Plain on the Hokkaido Island, thereafter it was taken up by the Hokkaido University[2),3]. Other studies have been made by the Japan Meteorological Agency[4], the Meteorological Research Institute[5),6),7] and the Nagoya University on Honshu.

According to the results of the studies made hitherto, the detailed mechanism of the low land snowfall is much more complex than generally expected, and it seems to have many interesting suggestions on precipitation physics. The authors think that it is impossible to clarify the mechanism of the local low land snowfall by ordinary synoptic analysis alone or by physical conception cloud alone. We are of the opinion that a three dimensional study of snow clouds in mesoscale is required. This paper will describe the results of observations which were made by the Cloud Physical Group in Hokkaido in 1964.

2. General Description

The surface weather map in Fig. 1 shows that a typical west-high east-low pressure pattern covered all Japan with the exception of Hokkaido Island on 25 Jan. 1963. On this day a heavy local snowfall of low land type was prevailing on the lower surface of the west coast of Japan. In the lower picture in the 850 mb level weather map in Fig. 1, it may be seen that cold air was present over North Korea. Owing to the existence of this cold air, westerly temperature wind was prevailing at the 850 mb level which corresponded to the height of cloud base. It may also be seen that a –12°C isotherm existed along the west coast of Honshu. According to the study of snow crystal growth, it has been shown by Houghton[8] that the temperature region around –15°C is most favourable for the growth of snow crystals. Considering the favourable temperature of the cloud and the westerly wind at the cloud

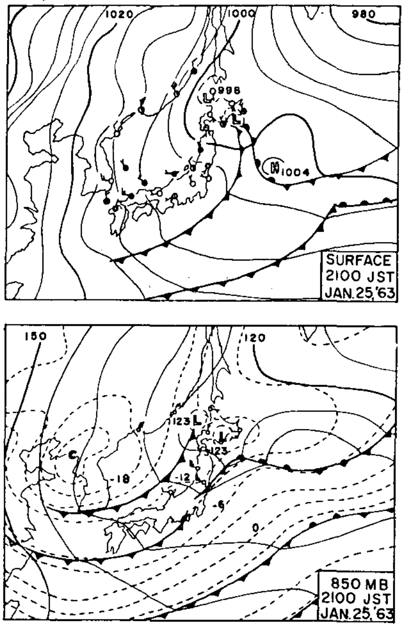

Fig. 1 Typical west-high east-low pressure pattern under which snowfall of low land type occurs.

level, it may readily surmized cloud physically that such a cloud would bring a heavy snowfall to the west of Honshu owing to the upslope of the mountain, but as to why the snowfall was localized to low land areas and to the particular locations, we have no explanation.

While an upper cold front was seen in the 850 mb level weather map from the south end of Korea to Honshu, it was unlikely that this cold front was directly related with the snowfall, because the front was at a considerable distance from the west coast of Honshu, and the prevailing wind had no ascending component to the front.

As may be surmized from the description above we can say that the snowfall in the winter monsoon season was not caused by fronts or cyclones, but was brought by the north-westerly wind itself.

3. Observation Network

The topography of Hokkaido Island is seen in Fig. 2, in which the location of the network is enclosed by a square. The north-westerly monsoon comes from the Ishikari Bay on the Japan Sea to our observation area as

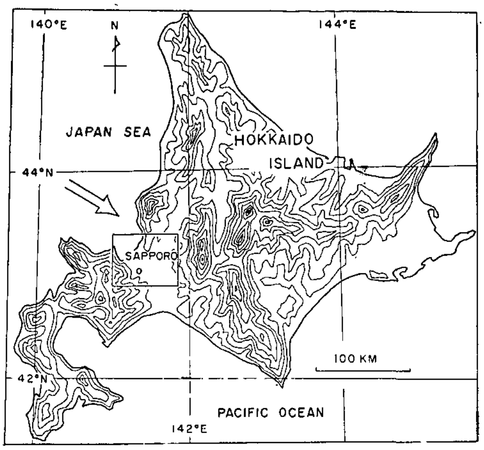

Fig. 2 Topography near observation network.

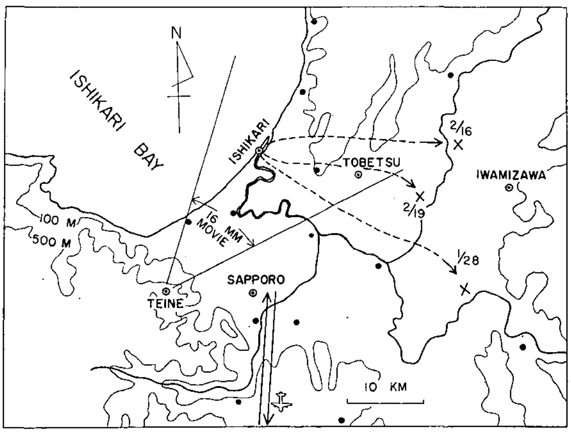

Fig. 3 Observation network, 1964 winter.

shown by an arrow in the figure. It may be assumed that the mountain region (higher than 1000 m) to the west of Sapporo and another group of mountains (higher than 1400 m) to the east of Ishikari Bay give some effect on the snow clouds which are carried in by the monsoon, as upslopes or as barriers against the monsoon wind.

A three dimensional observation network was organized in Ishikari Plain as shown in the table below and in Fig. 3, and the observations were made twice a day, viz., from 0800 to 1000 and from 1400 to 1600 for a month every day from 26 Jan., 1964.

Data gathering organization

Items	Places	Methods
Snow crystal shapes	14 high schools and 4 middle schools 6 main observation stations From Ishikari	Replicas of snow crystals Microscopic photographs and replicas Snow crystal sondes
Cloud distribution and shapes	6 main observation stations Mt. Teine Sapporo	Fish eye lens camera, Panoramic photographs A 16 mm time lapse movie camera
Vertical distribution of meteorological conditions of clouds	Ishikari Sapporo	UD-sondes Rawin-sondes
General surface meteorological conditions	All observation stations	
Aerial observation of clouds over observation area	Between Sapporo and Hakodate	Passenger flight airplane twice a day

In addition, data obtained by 60 railway stations in the Ishikari Plain were available. In Fig. 3, double marks and black dots show the location of main observation stations and high school observation points respectively.

4. Results

4.1 *Snowfall on* 27 *Jan.* 1964

Fig. 4 shows the surface and 850 mb level maps for the day. North Japan was covered by a pressure pattern of so-called west-high east-low type. There were no cyclones or fronts near Hokkaido but local snowfall of low land type occurred along the west coast of Hokkaido. As seen in the 850 mb weather map in Fig. 4, cold air was located on Sakhalin Island and a west wind was prevailing at the 850 mb level which corresponded to the cloud level on Hokkaido, and a −12°C isotherm was passing over the observation area.

Vertical distribution of temperature, wind and relative humidity with respect to water surface in the morning of this day are shown in Fig. 5. In the figure, thick solid lines, broken lines and dotted lines show the data from Sapporo, Vladivostok and Khabarovsk respectively. Khabarovsk was located to the windward of Sapporo on this day. It is noted that each

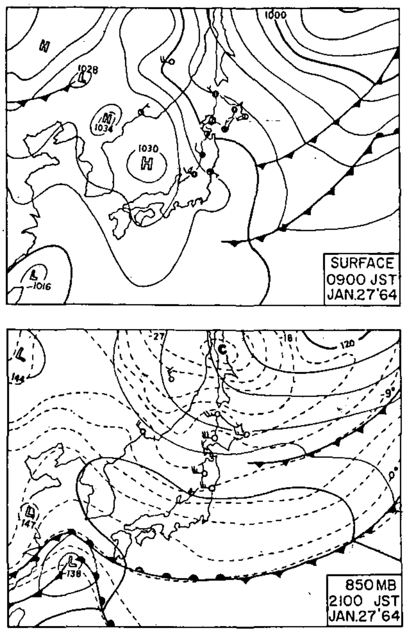

Fig. 4 Surface and 850 mb level weather maps, 27 Jan. 1964.

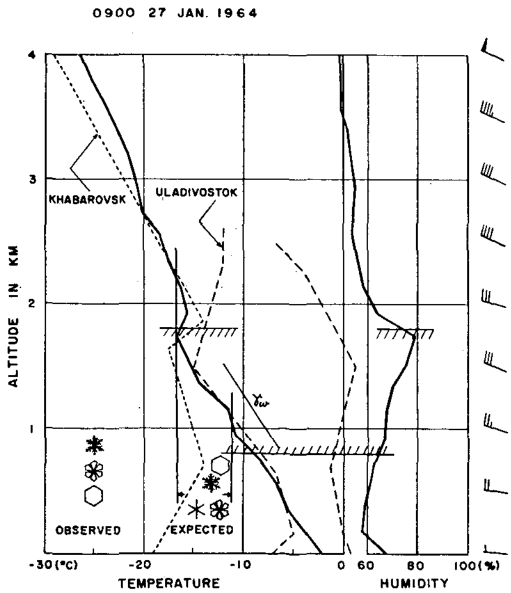

Fig. 5 Vertical distribution of temperature, humidity and wind. Types of snow crystals, observed and expected, 27 Jan. 1964.

profile of temperature had an inversion at about 1800 m altitude, and the temperature lapse rate below this level at Sapporo was almost the same as wet adiabat which is shown by a straight lint γ_w in the figure. It is seen also that the air below the inversion at Sapporo was much more moist than that at Khabarovsk. Wind direction was almost west at each level as shown in the right end of the figure. These facts suggest that a cold air mass came from Siberia, keeping its thickness nearly constant, in other words keeping its upper end at 1800 m, but was modified from the bottom strongly by warm sea water when passing over the Japan Sea. It is noted in the profile of humidity in Sapporo that the humidity decreased rapidly just above the 1800 m inversion level. From this rapid change in the humidity and the existence of temperature inversion at 1800 m altitude, we considered that this altitude indicated the height of the cloud top above Sapporo. The height of the cloud base was determined visually when a rawin-sonde balloon was sent up.

Since the vertical extent of the cloud was thus determined, it was possible to determine the temperature range of the cloud. And based on this, an expectation of the shape of snow crystals by means of Nakaya's diagram[9] was made. For this purpose, the result of crystal observation at the summit of Mt.Teine (1024 m altitude) was used, because microscopic photographs of snow crystals were best at the mountain, and this station was close to Sapporo.

In the case of Fig. 5, the temperature range of the cloud for the crystal growth was from $-17°C$ (1800 m) to $-11°C$ (1000 m). In this temperature range, it was expected that snow crystals would take the shape of hexagonal plate, sector and dendrite, as shown schematically at the bottom of the figure. These expected shapes were nearly the same as those of crystals at Mt. Teine as shown at the left bottom of the figure. Such good agreement means that the computation of the cloud top and base were correct and all the snow crystals originated from the cloud below the temperature inversion.

The horizontal distribution of snow crystal shapes are shown in Fig. 6. Crystal shapes described by thick lines mean that the snow crystals were considerably rimed. It may be seen in the figure that snow crystals observed near the coast of Ishikari Plain were all rimed crystals or graupel. In contrast to this, snow crystals observed at inland and at Mt. Teine were not rimed. The intensity of the snowfall equivalent to water was several mm per hour in the northeast half of the observation area, but no snowfall was observed in the south half of the area. It is noted that low land obser-

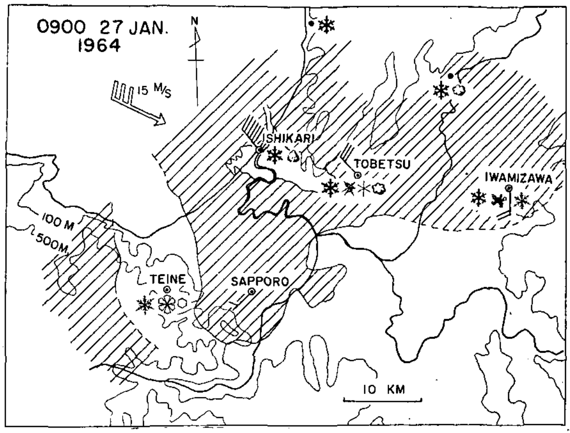

Fig. 6 Horizontal distribution of clouds and snow crystals, 27 Jan. 1964.

vation stations where snow crystals were observed were all covered by clouds. There were no clouds above Mt. Teine.

4.2 *Snowfall on* 28 *Jan.* 1964

On the next day, 28 Jan. the west-high east-low pressure pattern became loose as seen in the upper map of Fig. 7. From such a loose pattern, no snowfall was expected, however a snowfall of low land type actually occurred in the Ishikari Plain. An upper cold front is seen to the south of Hokkaido in the lower map (850 mb map) of Fig. 7, but it is considered that this front had no effect on the snowfall on the west coast of Hokkaido, because the front was far from the west coast leeward and the wind direction at this level was parallel to the front line. Cold air existed near North Sakhalin identical to that in Fig. 4.

The vertical distribution of meteorological conditions is shown in Fig. 8. In the figure, thick solid lines show the data by rawin-sonde from Sapporo. Thin solid and dotted lines show the data by radio-sondes of up and down course type, (so-called UD-sonde, of Kimura [10],) from Ishikari. It may be seen in the vertical distribution of temperature that each profile shows a temperature inversion near the 2200 m altitude and this altitude coincides with that of the rapid decrease in humidity except in the case of downward course of UD-sonde. But the hygrometer of UD-sonde had a large time lag. Therefore height of cloud top was determined as 2200 m. The cloud base was determined visually.

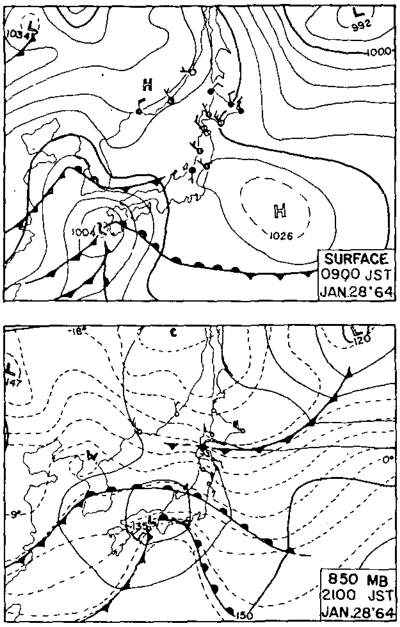

Fig. 7 Surface and 850 mb level weather maps, 28 Jan. 1964.

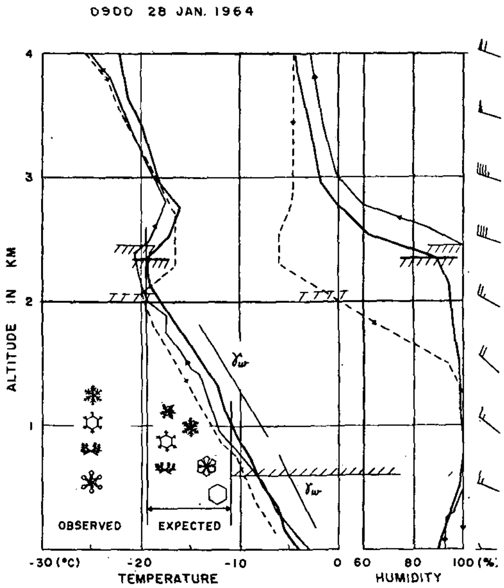

Fig. 8 Vertical distribution of temperature, humidity and wind. Types of snow crystals, observed and expected, 28 Jan. 1964.

The vertical extent of the cloud higher than the summit of Mt. Teine thus determined corresponds to a temperature range from −11 to −23°C. It was expected from the temperature range that snow crystals of radiating dendritic, spatial dendritic, dendritic, plate with dendritic branches, sector and plate shapes would be observed at Mt. Teine, as shown schematically at the bottom of the figure. The actually observed snow crystal shapes are shown at the left bottom. Noting the shape at the end of branches of observed snow crystals, it is considered that the type of observed snow crystals were nearly the same as the expected type.

The observation area was covered completely by clouds as shown in Fig. 9 and snow crystals were observed at all observation points. But the snowfall was very light in the north-east half of the observation area and was very heavy in the south-west half, reaching 30 mm (equivalent water) per hour at Sapporo. However the tendency for rimed crystals to fall near the coast area and non-rimed crystal to fall inland was the same as in the case of 27th.

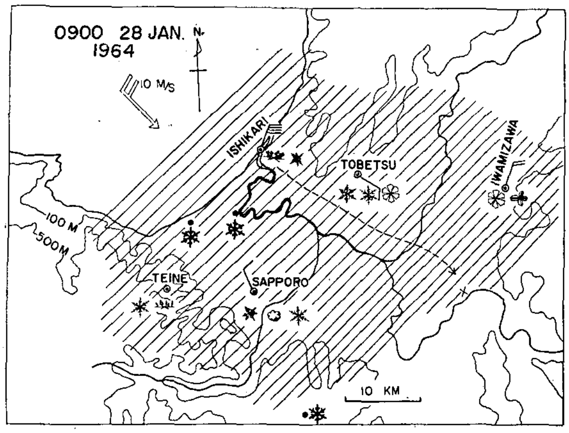

Fig. 9 Horizontal distribution of clouds and snow crystals, 28 Jan. 1964.

The broken arrow from Ishikari to the east in the figure shows the computed flight course of a "Snow Crystal Sonde" by Magono and Tazawa[11]. The course was computed by means of the vertical distribution of wind which was measured by a rawin-sonde from Sapporo. The cross-mark near the end of the arrow shows the point where the snow crystal sonde was actually recovered.

Simultaneous observation by UD-sonde and by snow crystal sonde was made from Ishikari. These sondes followed almost the same course. By means

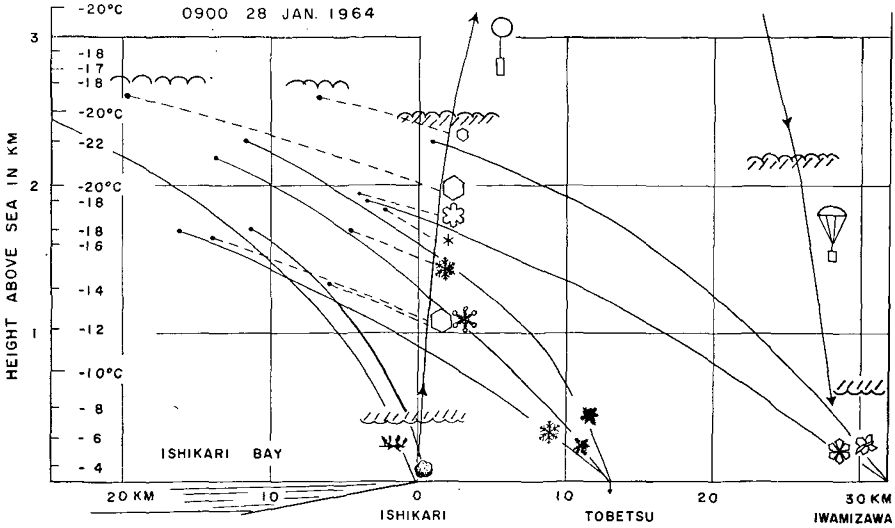

Fig. 10 Vertical structure of snow clouds and trajectories of falling snow crystals.

of the data obtained by the sondes, the vertical structure of a snow cloud was studied. Let us consider a vertical cross-section of the snow cloud on a straight line from Ishikari, via Tobetsu to Iwamizawa, as shown in Fig. 10. The line was parallel to the direction of the prevailing wind at the cloud height. In the figure the horizontal axis indicates the distance from the coast (Ishikari) in the inland direction. The vertical axis indicates the height above sea level, and the temperature distribution which corresponded to the height. A UD-sonde and a snow crystal sonde were released from Ishikari along the curve shown by a thick upward arrow, and reached the 500 mb level (about 5000 m altitude), then dropped near Iwamizawa as indicated by a downward arrow at the right end of the figure. The estimated cloud top and observed cloud base are also shown crossing the ascent and descent courses.

Shapes of snow crystals observed at the ground are shown schematically for each observation station. By the use of fall speed of snow crystals of each type and by the use of vertical distribution of wind velocity, it was possible to trace the falling trajectory of each snow crystal, as shown by thin solid curves from the observation station. By means of Nakaya's diagram, the altitude where the snow crystals of each type began to form could be computed, as shown by black dots at the end of each trajectory. The type of snow crystals obtained at each level by the snow crystal sonde are shown schematically at each level along the ascending course of the sonde. The computed trajectory of the snow crystals are indicated by broken curves. The trajectory was determined by the same method as in the case of ground observation. It is noted that the snow crystals observed by the snow crystal sonde at cloud level were not rimed.

It is seen clearly in Fig. 10 that all snow crystals observed, had already begun to form over the Ishikari Bay. It may also be seen that the majority of observed snow crystals were born at a temperature range between −14 and −20°C. This is a reasonable result, because this temperature range is most favourable for the growth of snow crystals, as pointed by Houghton. It follows of course that snow crystals were born at levels lower than the cloud top. Therefore, the height of the cloud top above the sea was estimated by the initial point of snow crystals as shown in Fig. 10. It is noted that the top of clouds above the sea was a little higher than that of the clouds above the ground. Here it should be noticed that the temperature scale at the left end of Fig. 10 was determined by the data obtained by the UD-sonde released from the ground.

4.3 *Snowfall on* 16 *Feb.* 1964.

On this day snowfall of the low land type occurred, and the synoptic situation shown by Fig. 11 was almost the same as those on 27, 28 Jan. 1964. The vertical profile was also similar to those on 27th and 28th as shown in Fig. 12.

The horizontal distribution of cloud cover and of snow crystals are shown in Fig. 13. It may be seen in the cloud distribution that three bands of clouds (left bottom, center and upper right) were distributed from west to east parallel to the upper wind direction. The non cloud band area near Sapporo perhaps was affected, to some extent, by the descending air current which came from the western mountain area. The snowfall intensity was smaller than 6 mm (equivalent water) per hour.

Fortunately TIROS No. 3 covered Hokkaido two hours after our observation as shown in Fig. 14. In the figure, the cloud pattern of streak shape parallel to west wind direction is seen near Hokkaido (at the right hand of the figure). It is noted that such clouds had already developed densely half way between Siberia and Hokkaido. In this case, mountains on the west coast of Hokkaido seemed to have no effect on the formation of the clouds; the

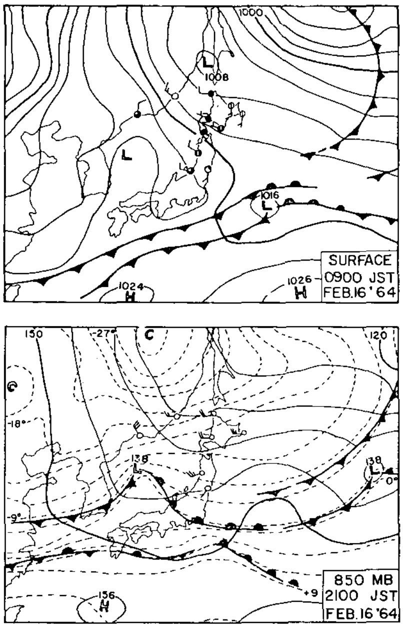

Fig. 11 Surface and 850 mb level weather maps, 16 Feb. 1964.

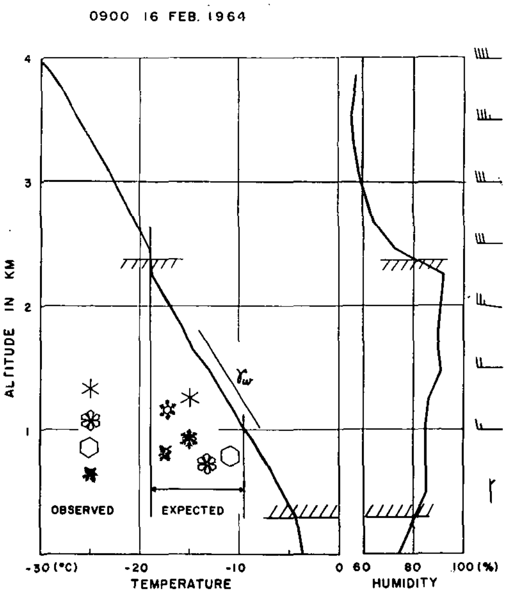

Fig. 12 Vertical distribution of temperature, humidity and wind. Types of snow crystals, observed and expected, 16 Feb. 1964.

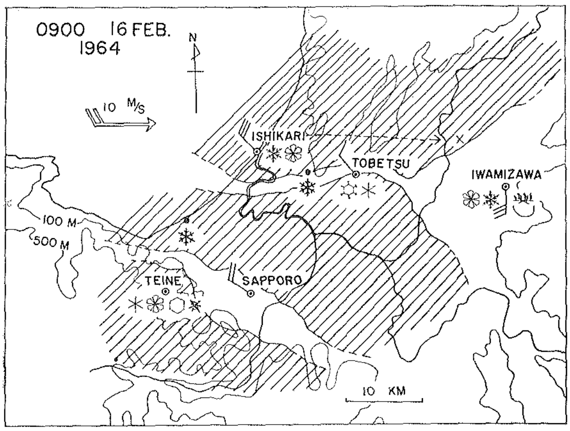

Fig. 13 Horizontal distribution of clouds and snow crystals, 16 Feb. 1964.

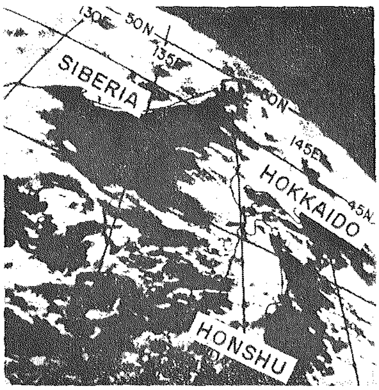

Fig. 14 Cloud distribution near Hokkaido by TIROS picture, 1130 16 Feb. 1964.

clouds disappeared some where over Hokkaido. Other clouds of similar pattern occurred again over the Pacific Ocean to the south-east of Hokkaido. This second formation of clouds strongly suggests that ascending air due to mountain upslope was not required for the formation of cloud in winter monsoon season.

4.4 *Snowfall on* 19 *Feb.* 1964

On this day, snowfall of low land type occurred at the observation area, although it was light. The surface and 850 mb level weather maps are shown in Fig. 15. It may be seen that the pressure pattern, isotherms and wind

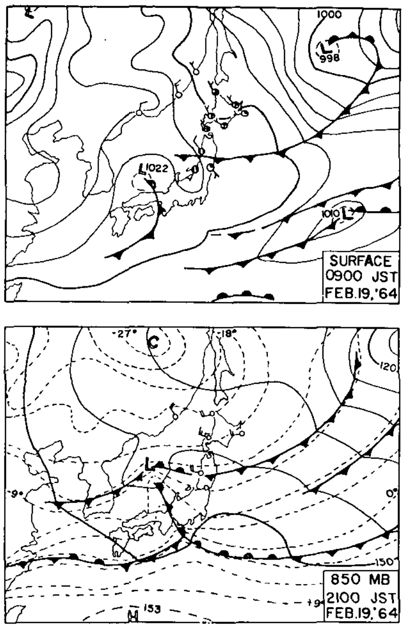

Fig. 15 Surface and 850 mb level weather maps, 19 Feb. 1964.

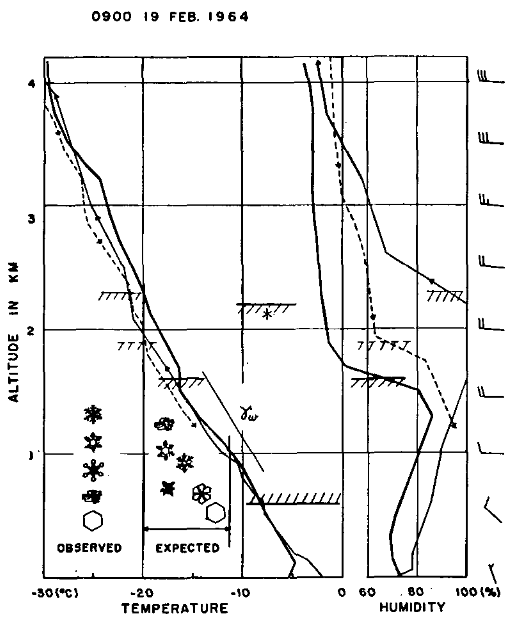

Fig. 16 Vertical distribution of temperature, humidity and wind. Types of snow crystals, observed and expected, 19 Feb. 1964.

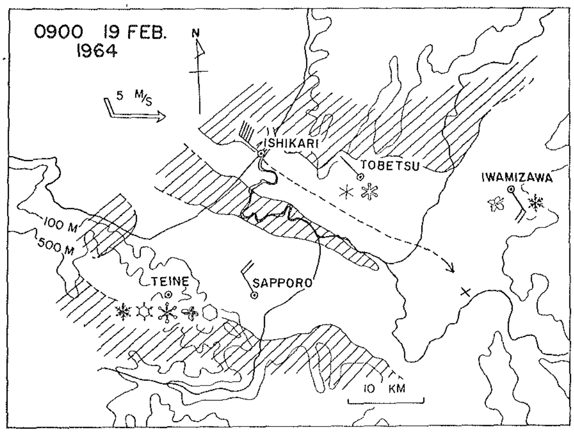

Fig. 17 Horizontal distribution of clouds and snow crystals, 19 Feb. 1964.

Fig. 18 Cloud distribution near Hokkaido by TIROS picture, 1044 19 Feb. 1964.

direction were all similar to those described hitherto. The vertical distributions of temperature, humidity and wind are shown in Fig. 16. The tendency was also nearly the same as those on 27, 28 Jan. and 16 Feb. but it is noted that the height of cloud base was considerably lower and irregular. This perhaps was because the cloud area was very small as shown in Fig. 17. In such a case, it is doubtful that the rawin-sonde from Sapporo penetrated the cloud layer even if UD-sonde from Ishikari penetrated some cloud layers. A cloud of thin band type was seen at the center of the observation area. The TIROS picture also showed snow clouds of streak type as shown in Fig. 18, in which clouds of curved band shape reached Hokkaido.

5. Change of Snow Clouds near the Seashore

Almost always during the observation period, clouds which penetrated into the Ishikari Plain from the sea were observed by a 16 mm time lapse movie camera at the summit of Mt. Teine with particular emphasis on their change in form when arriving at the seashore. When the summit was enclosed by clouds, observation by movie camera was difficult, however many pictures obtained thus showed the following characters of cloud form.

1. Clouds in the monsoon period always were of band shape. This was also shown by the horizontal distribution and the TIROS pictures.

2. When clouds arrived at the seashore, they changed the form of their tops from a scalloped type to a smooth type and their tops became lower and diffused. It was frequent that the clouds disappeared after they arrived inland, although the clouds observed were not strong in nature.

3. It was usual that a snowfall had already occurred before the snow clouds reached the shore, but this snowfall did not reach the sea surface. However it was observed that the snow suddenly reached the ground surface when the snow clouds arrived at the seashore.

4. The height of cloud top seemed to coincide with that computed by the temperature inversion.

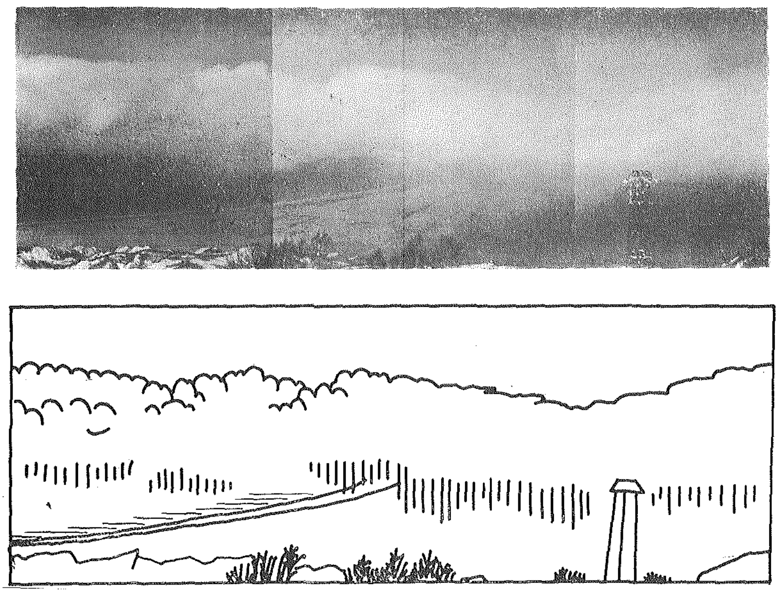

Fig. 19. Change of cloud near seashore, from convective to diffused type, 6 Feb. 1964.

During the observation periods on 27, 28 Jan. and on 16, 19 Feb., Mt. Teine was covered by clouds, however the panoramic picture which was taken on 6 Feb. showed the 3 characters described above, because the mountain was not covered by clouds. The panoramic picture is shown in Fig. 19. Active snow clouds were coming in from the left. When they arrived at seashore, the top of the cloud changed from a scalloped type to a smooth type. This change suggests that they were totally glaciated. It may also be seen in the figure that the snow clouds became diffused and snowfall began to reach the ground a little after the clouds crossed the seashore.

It is noted that the cloud pattern was quasi-stational with respect to the seashore but the constituent of the clouds were always transported from the sea to the ground. Such cloud conditions continued for several hours, thus local snowfalls on band shape areas were brought to the Ishikari Plain.

6. Considerations

During the observation period, no heavy snowfall occurred, however several snowfalls of low land type were observed. The results obtained may be summarized as follows.

1) Invariably cold air was located to the north of Hokkaido. Owing to this, uniform west wind was prevailing when snowfall of low land type occurred. And −12°C isotherm passed over the observation area at a 850 mb level weather map. From the conception of cloud physics, it is considered that this relation between the wind and temperature is a favourable condition for the formation of snowfall, if the cloud layer is above 850 mb level, even when there is no particular ascending air current due to fronts or upward slope of mountains.

2) During snowfall of low land type, no cyclones or fronts were observed near Hokkaido.

3) The top of clouds usually coincided with the top of temperature inversion, and the computed height of layer where snow crystals began to form was lower than the cloud top. These facts mean that the clouds and the snow crystals were all developed within the cold mass, in other words, under the surface of cold front which came from Siberia.

4) Clouds were already formed half way between Siberia and Hokkaido, and snow crystals began to form above the sea, in other words, before the clouds arrived over the land. However it was occasionally observed that snowfall began to reach the ground when the clouds arrived the seashore.

The facts 2), 3) and 4) strongly suggest that snowfall of low land type was not brought about by the effect of fronts, cyclones or upslope of mountains.

5) Snow clouds were distributed in several band areas parallel to the direction of prevailing wind. It seems that the snowfall areas generally coincided roughly with the cloud cover distribution, but had no direct relation with the topography.

Considering the facts described above, the following model was proposed for the mechanism of snowfall of low land type, as shown in Fig. 20 which shows the vertical section of a snow cloud parallel to the wind direction.

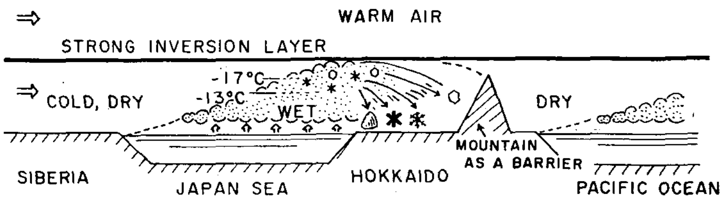

Fig. 20 Proposed model of mechanism for snowfall of low land type in winter monsoon season.

The height of the upper end of temperature inversion on the west coast of Hokkaido is some times lower but at other times is higher than that on Siberia. And there seems to be no reason why the height changes. Therefore it is conjectured that the upper surface of cold air mass from Siberia does not change its height and arrives over Hokkaido. However the lower end of temperature inversion may become higher as the air mass approaches Hokkaido, because of the heat and vapor supplied by the warm sea water surface. Thus the depth of the cloud which was modified by vapor supply from below becomes a cloud, as shown in Fig. 20. Therefore such a cloud is a kind of steam fog layer. Such a cloud layer steam fog was observed in a small scale by Kikuchi[12] when cold air flowed out to Ishikari Bay from the Ishikari Plain on a clear cold night.

As a cold air mass from Siberia passes over the Japan Sea, the vertical extent of the cloud layer increases. When the upper end of the cloud reaches at temperature region from −13 to −17°C, the cloud becomes glaciated and snow crystals in the cloud grow rapidly in dendritic form. At about the time when the cloud arrives over Hokkaido Island, its top reaches the upper surface of the cold air mass (upper end of temperature inversion). However, this may not be the case on Honshu, because the width of sea surface to the west of Honshu is much greater than that of Hokkaido.

Above a warm sea surface, the falling snow crystals may be suspended, to some extent by ascending air, but above the cold ground surface of Hokkaido, there is no ascending air. This may be the reason why snowfall seems to begin to reach the ground surface when the snow cloud passes over the seashore. In this case, heavier snow particles such as graupel or rimed snow crystals fall first near the coast, then lighter non-rimed snow crystals fall inland at a later time. After all snow crystals fall, the snow cloud disappears until it reaches the mountain area in the center of Hokkaido Island. If the snow clouds were dense and strong enough to reach mountain area, the clouds may develop again by the ascending air current along the upslope of the mountains.

Because almost all vapor is exhausted as snow crystals fall on the west side of the mountain, the air may be very dry after it goes over the mountain and may form again as low fog layers on the Pacific Ocean as shown in the right end of Fig. 20.

It is considered by Kuettner[13] that under a strong vertical wind shear, a cloud pattern parallel to the shear occurs, but in the case of our observation no usual wind shear, either vertical or horizontal was detected near the cloud level, but wind velocity was nearly the same from 500 to 4000 m altitude, or increased gradually with the ascent. The cloud top was always lower than 2500 m. The observation of the previous season showed the same results. Therefore the authors are of the opinion that wind shear is not important but the strong wind itself is important. On the other hand it is considered that a line of convection is produced and accelerated by a vertical wind shear. Therefore the authors consider that wind shear between sea surface and lower layers may be important in the formation of such a line of convection, in other words in the formation of a cloud pattern of band shape.

If the pressure pattern of typical west-high east-low type as shown in Figs. 4, 7, 11 and 15 continues, snow clouds of band shape may continue to bring snowfall of band shape area to the west coast of Hokkaido. This snowfall does not require any ascending air current by cyclones, fronts or mountains. The clouds produced in such monsoon season are very low. Therefore sometimes, the mountains may act as barriers, then the cloud may avoid the mountain area and concentrate on low band areas. If such is the case, the snowfall in low land areas may be heavier than that in the mountain areas. And the snowfall becomes localized in the band shaped area.

The model of the mechanism for the snowfall of low land type was derived from the observational results on the west coast of Hokkaido. The width of Japan Sea between Hokkaido and Siberia is narrow. But the width is much greater in the case of Honshu Island. Therefore it is considered that the mechanism of snowfall on the west coast of Honshu may be, to some extent different, and perhaps snow clouds may be more modified than that in Hokkaido.

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