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Precipitating Snow Clouds during Winter Monsoon Seasons Influenced by Topography of the Shakotan Peninsula, Hokkaido Island, Japan (SHAROP)

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Abstract

The radar observations carried out on the Shakotan Peninsula, Hokkaido, Japan, indicated that the direction of movement of the precipitation echoes from snow clouds invading from the northwest to southeast had a tendency to shift towards the east, by about 10 degrees near the mountainous regions, when compared to the echoes over the center of the Ishikari Bay. This tendency was the same as in the case of the echoes from the north-northwest to south-southeast. It was considered, therefore, that the tendency seemed to reflect the influence of the mountainous regions. To estimate the topographical effect of the mountains around the peninsula, numerical experiments using Lavoie's mesoscale model were carried out. The experiments indicated also that the wind direction in a mixed layer shifted eastward by about 10 degrees near the mountainous regions to the west of the Ishikari Plain as compared to that in the center of the Ishikari Bay. Considering the fact that radar echoes of precipitating snow clouds move along the mean wind direction in the mixed layer, this result agrees well with the radar observations. It is expected therefore that the results obtained by this study will provide valuable informations for the nowcasting of snowfall in the Ishikari Plain including Sapporo City.

Key Words: Snow clouds, Winter monsoon, Topographic effect, Radar observations, Nowcasting.

1. Introduction

The Ishikari Plain located on the west coast of the Hokkaido Island, Japan, extends along the wind direction of the northwest winter monsoon and has a width of about 40 km and a length of 60 km. There are mountainous regions to the west and north of the plain, and the Shakotan Peninsula juts out in a northwesterly

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direction parallel to the prevailing winter monsoon wind direction. Ishikari Bay is surrounded by these regions. The areas, including Sapporo which has a population of 1.5 million, are concentrated in the Ishikari Plain, so that the snowfalls, especially of the monsoon type, have a great influence on the activities of these urban areas. During the winter monsoon season, the snowfalls are characterized by band shaped snow clouds almost parallel to the 850 mb wind direction (Higuchi, 1963; Magono et al., 1965, 1966; Kikuchi, 1967, 1973; Nanasawa, 1975), which invade the west coast of the Ishikari Plain, and frequently bring heavy snowfalls to limited regions on the plain.

From the satellite pictures by NOAA, GMS, and LANDSAT it is often noticeable that the direction of the band shaped snow clouds shifts eastwards near the Shakotan Peninsula. From these pictures, therefore, it is expected that the mountainous regions stretching out on the westside of the plain would affect the invading direction of the precipitating snow clouds.

Up to the present, radar observations around the Ishikari Plain have been carried out at Sapporo, however, it is impossible to scrutinize the precipitating snow clouds near the Shakotan Peninsula, since the mountainous regions obscure the view of PPI scanning of the radar. Thus, we carried out observations of the precipitating and invading snow clouds by means of our mobile weather radar set up at the Shakotan Peninsula. The observations referred to as SHAROP (Shakotan

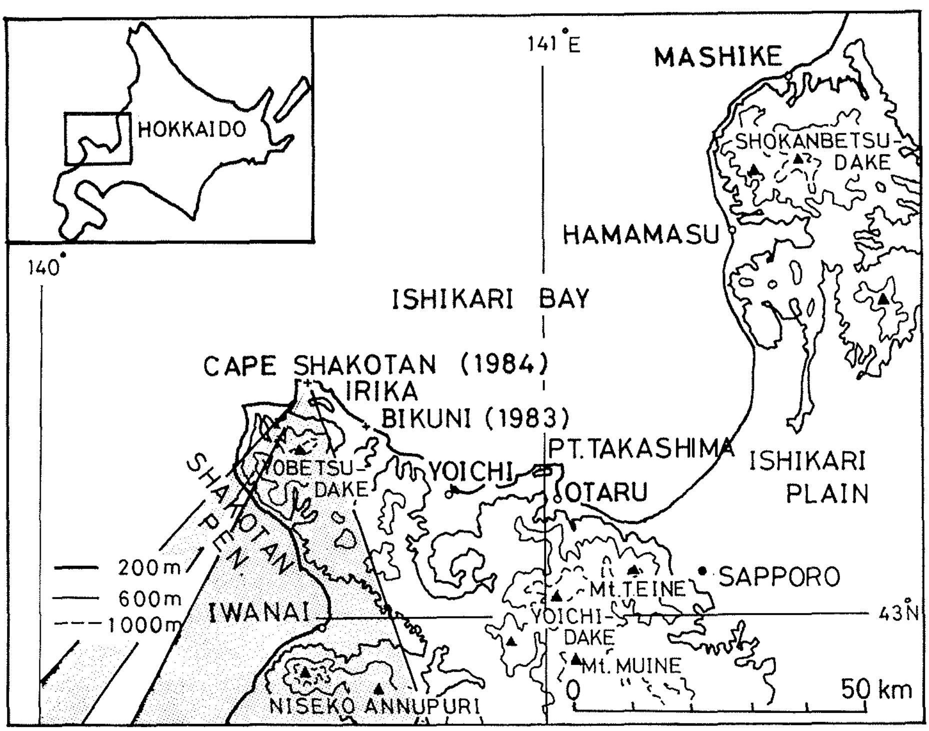


Figure 1. Map around the radar observation site. Shaded areas show shadow zones.

Radar Observation Project) were made from January through to March, 1983 and 1984.

On the other hand, to estimate the mountainous topographical effect around the Shakotan Peninsula, we ran numerical experiments using Lavoie's mesoscale model (1972). This model was developed in order to study "Lake Effect Snow Storms" of Lake Erie in the U. S. A., during cold-air outbreaks in the mid-winter season. It would appear that similar processes of modification of the atmosphere should operate in Lake Erie and the Japan Sea during the winter monsoon seasons. Estoque and Ninomiya (1976) have already applied this model to simulate the snowfalls along the coast line of the Japan Sea, and they showed that results of the model agreed with the observation results. Thus, we applied this model to a 2000-point grid mesh centered on the Ishikari Bay, with a grid spacing of 5 km × 5 km around the bay and the peninsula.

This paper will describe the results of the radar observations and a comparison with the numerical experiments.

2. Radar observations

Radar observations were carried out from January through to March, 1983 at the Point Ohgon in Bikuni (43°18′N, 140°37′E) and in 1984 at the Cape Shakotan in Irika (43°22′N, 140°29′E). The Point Ohgon is located in the center of the northeast shore of the peninsula and the radar scanner was set up on the panoramic view stage of the cliff 70 m above the sea level. Cape Shakotan is located at the northern point of the peninsula and the radar scanner was installed on an assembled iron tower 3 m in height close to the light-house on the cliff 100 m above sea level. Both radar sites are shown in Fig. 1. During the observations, PPI scans

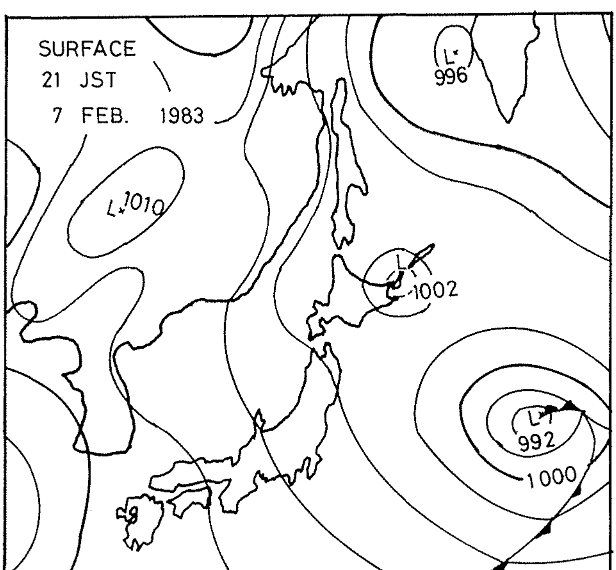


Figure 2. Surface weather chart. 2100 JST Feb. 7, 1983.

of radar echo patterns were continuously recorded on films by a 35 mm motor driven camera at 5 or 10 minute intervals. Trajectories of echoes of precipitating snow clouds were analyzed from a series of these photographs.

a. Case 1 ; 16 : 15 JST February 7, 1983

As seen in the surface weather chart at 21 : 00 JST Feb. 7, 1983 in Figure 2,

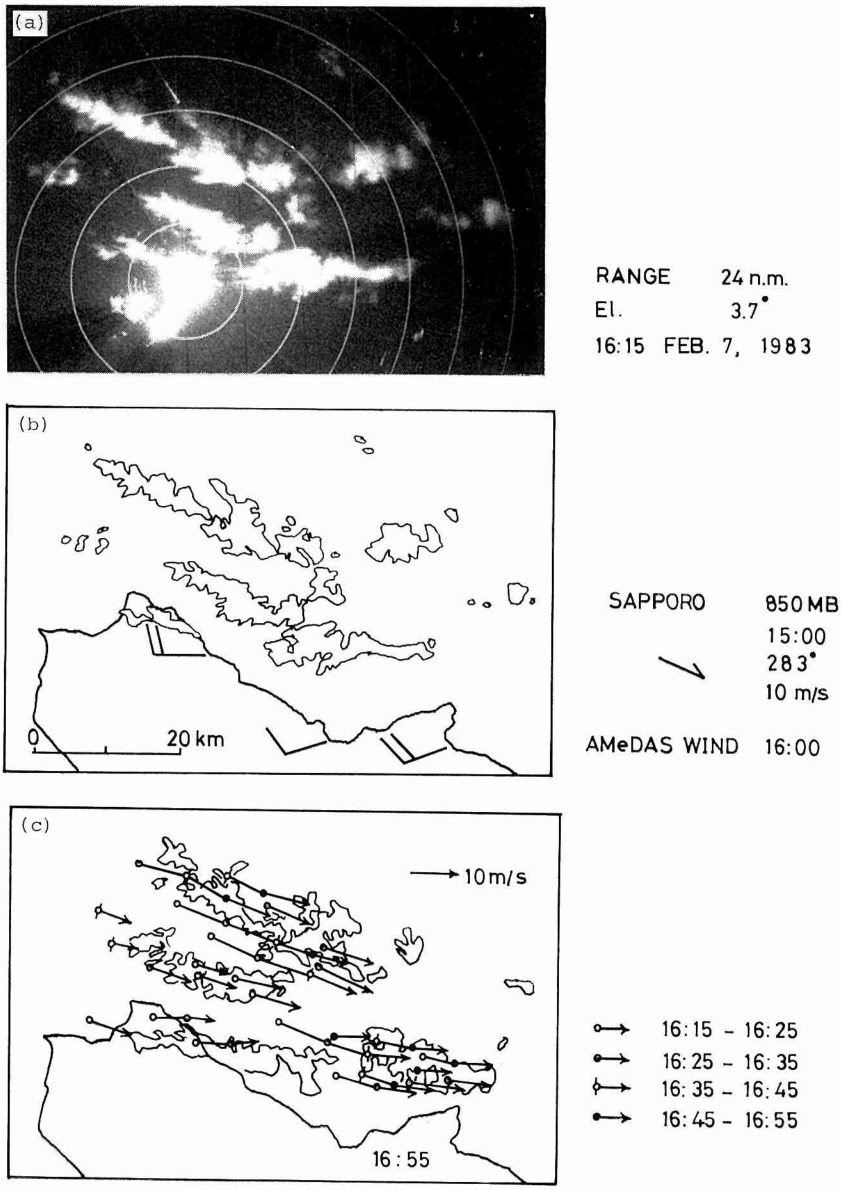


Figure 3. Radar observation on Feb. 7, 1983. (a) Radar echoes at 1615 JST. (b) Echo sketches at the same time as (a) and surface wind. (c) Displacement of echoes at 10 min. intervals from 1615 to 1655 JST.

the pressure gradient around Hokkaido Island was weak with a weak westerly or west-northwesterly wind at the observation site. Figure 3 (a) shows an example of radar echoes obtained at the Point Ohgon radar site at 16 : 15. In this figure, each range mark indicates 4 n. miles, the elevation angle is 3.7°, and the height of precipitation echoes is 1 to 2 km above the sea level. Figure 3 (b) shows the echo sketches at the same time of Figure 3 (a). From these figures, we note that the direction of the echoes is different far from the Cape Shakotan (294° to 114°) and just north of the Point Takashima (273° to 93°) located on the west side of Otaru. Further, the direction of movement of echoes at each 10 minute intervals from 16 : 15 to 16 : 55 is plotted in Figure 3 (c). On some distance to the north

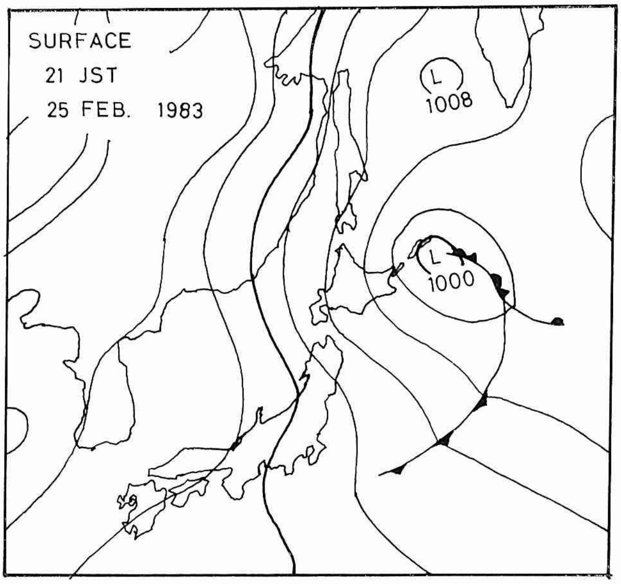


Figure 4. Surface weather chart. 2100 JST Feb. 25, 1983.

Figure 5. NOAA-6 IR picture around Hokkaido Island. 1900 JST Feb. 25, 1983.

of Cape Shakotan, this direction was from 283° to 103°, paralleled with the wind direction of 850 mb level observed on 15 : 00 at the Sapporo District Meteorological Observatory as shown in Figure 3 (b). On the other hand, the echoes to the north of the Point Takashima was from 273° to 93° ; the difference between both directions being approximately 10°.

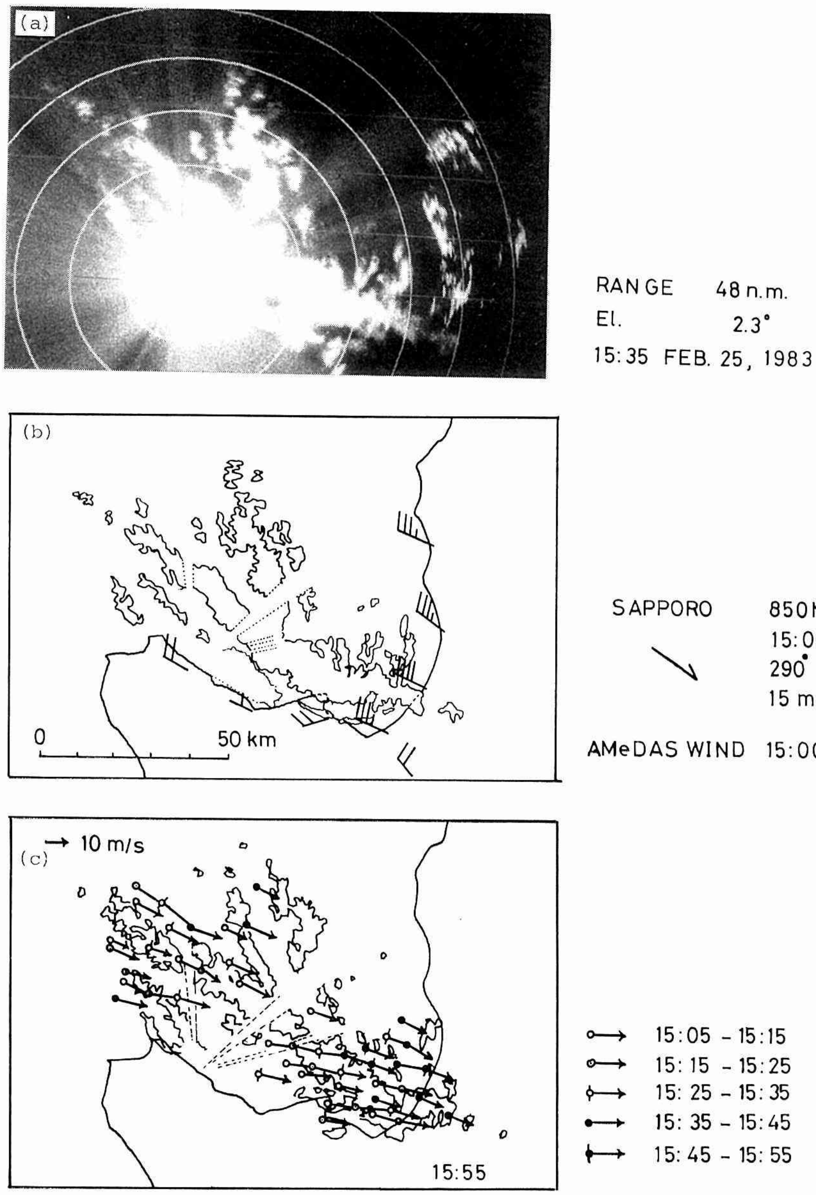


Figure 6. Radar observations on Feb. 25, 1983. (a) Radar echoes at 1535 JST. (b) Echo sketches at the same time as (a) and surface wind. (c) Displacement of echoes at 10 min. intervals from 1505 to 1555 JST.

b. Case 2 ; 15 : 35 JST February 25, 1983

A surface weather chart at 21 : 00 JST Feb. 25, 1983 is displayed in Figure 4. Comparing with the previous case, a pressure pattern around Hokkaido Island was a typical winter monsoon type, that is to say, high pressure to the west and low to the east, so that the isobars were straight from north to south over Hokkaido Island. Watching the NOAA-6 IR picture as shown in Figure 5 taken at 19 : 00 JST on that day, a typical streak cloud has spread over the Japan Sea and a relatively large band-shaped cloud has invaded along the Shakotan Peninsula to the Ishikari Plain. Figure 6 (a) shows radar echoes observed at the Point Ohgon radar site at 15 : 35. In this figure, each range mark indicates 8 n. miles, and the elevation angle is 2.3°. From Figure 6 (a) and (b), it seems that two cloud bands coming from 315° and 340° have converged at Yoichi (westwards of the Point Takashima) and subsequently the direction of echoes changed to 282°. The direction of movement of echoes at 10 minute intervals from 15 : 05 to 15 : 55 is plotted in Figure 6 (c). It is apparent that for echoes invading from the center of the Ishikari Bay toward the Ishikari Plain this direction (approximately from 295° to 115°) was nearly the same as 850 mb level wind direction at Sapporo, shown to be 290° in Figure 6 (b). However, at around the Point Takashima and Otaru areas, the direction of movement of echoes was from 280° to 100°, giving a difference between both directions of approximately 15°.

c. Case 3 ; 11 : 00 JST February 4, 1984

The weather pattern on 09 : 00 JST Feb. 4, 1984 showed the most typical winter monsoon type as seen in Figure 7. Figure 8 shows a visible cloud picture around Hokkaido Island taken by NOAA-7 at 13 : 50 JST Feb. 4, 1984. As for

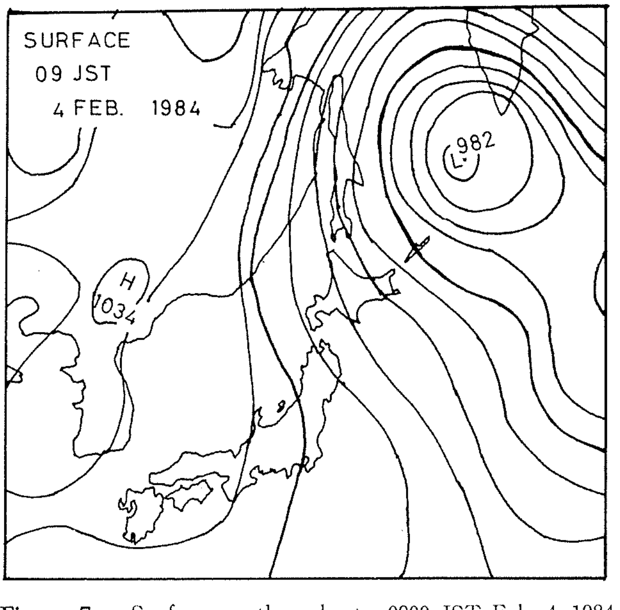


Figure 7. Surface weather chart. 0900 JST Feb. 4, 1984.

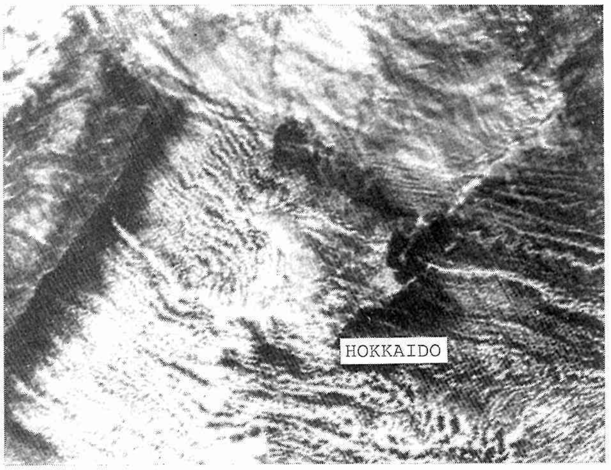


Figure 8. NOAA-7 VIS picture around Hokkaido Island. 1350 JST Feb. 4, 1984.

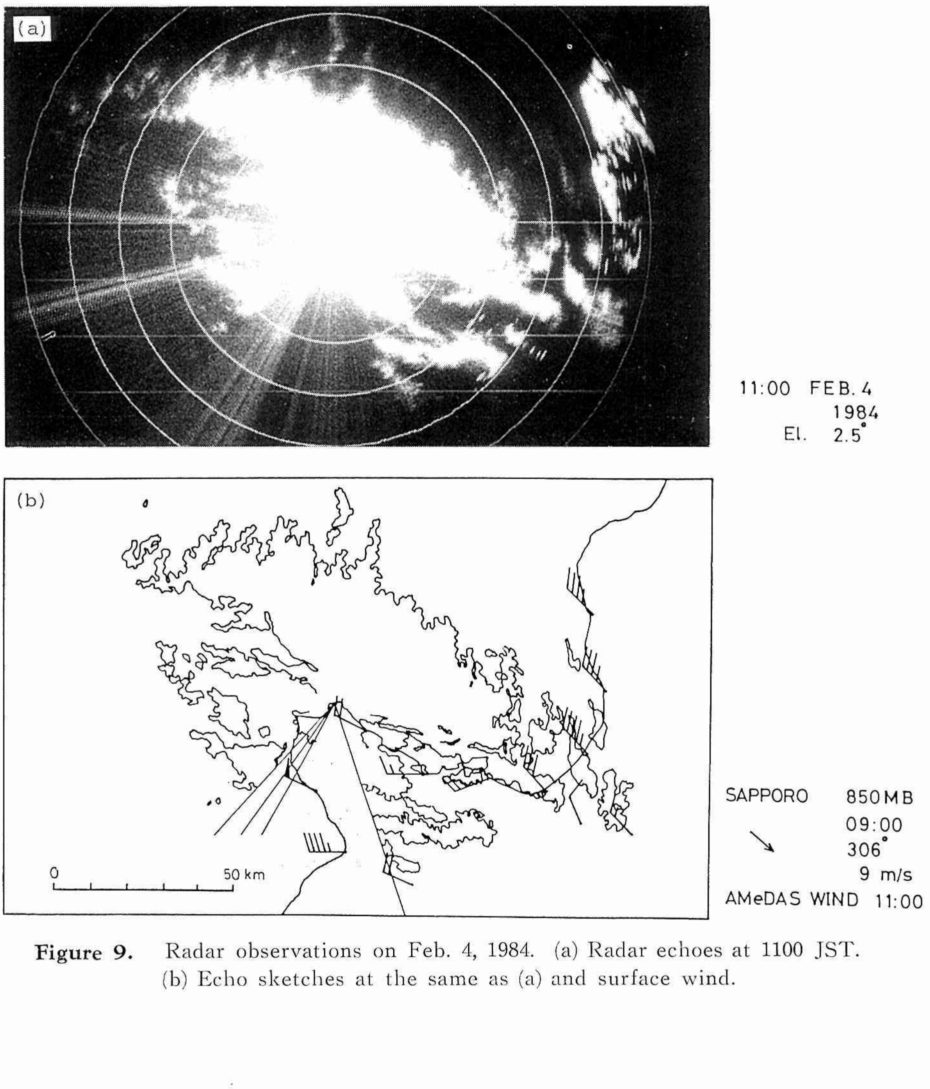


Figure 9. Radar observations on Feb. 4, 1984. (a) Radar echoes at 1100 JST. (b) Echo sketches at the same as (a) and surface wind.

case 2, Feb. 25, 1983, the streak clouds have spread over the Japan Sea and a large meandering band shaped cloud has invaded along the Shakotan Peninsula to the Ishikari Plain. One of radar echo photographs observed at the Cape Shakotan radar site at 11 : 00 JST corresponding to Figure 8 is shown in Figure 9 (a) and the echo sketch in Figure 9 (b). Based on these echoes, the directions of movement of individual echoes were analyzed at 5 minute intervals from 10 : 00 to 11 : 00 and the results are displayed in Figure 10 (a). Each segment shows the direction and distance of precipitating snow clouds. It is recognized that almost all echoes have been displaced from northwest to southeast, that is, the upper left corner to the lower right corner. To determine the direction of movement of individual echoes around the peninsula, all echoes shown in Figure 10 (a) were divided into three groups by their movement angles as seen in Figure 10 (b) to (d). As seen clearly in the figure, echoes having an eastward component, that is to say, from between 270° and 280° to between 90° and 100° as shown in Figure 10 (b), were more frequent around the Point Takashima and the westside of the Shakotan Peninsula. On the contrary, echoes having a southward component, that is from larger than 300° to larger than 120°, were seen scattered over the Japan Sea far from the peninsula as depicted in Figure 10 (d). Average directions of movement of the echoes were from 293° to 113° over the center of the Ishikari Bay, from 283° to

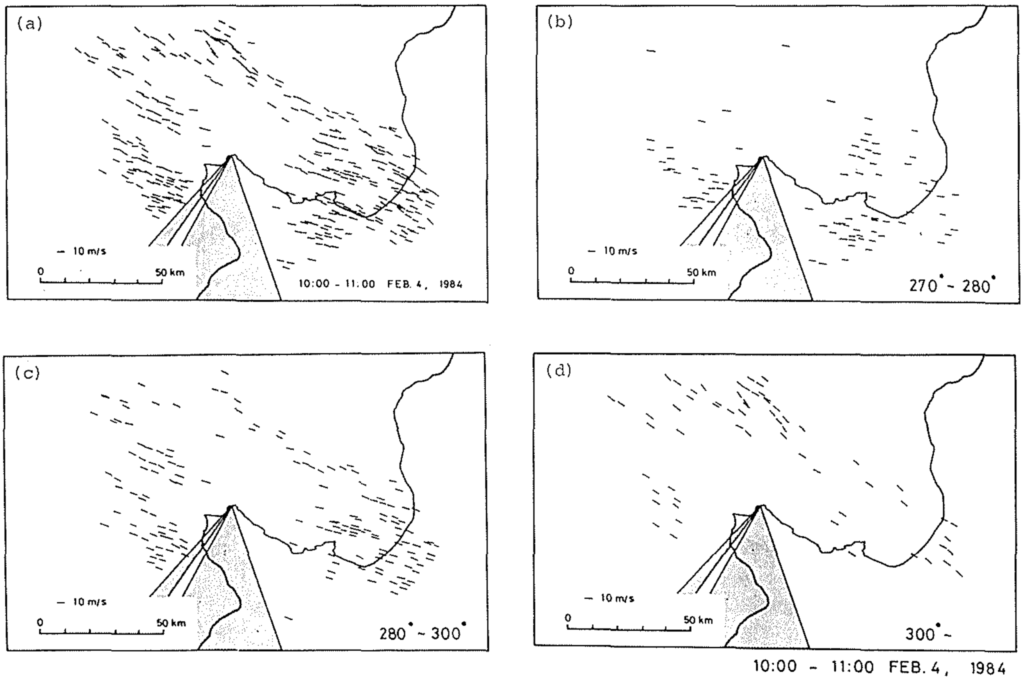


Figure 10. Displacement of echoes on Feb. 4, 1984. (a) Displacement of echoes at 5 min. intervals from 1000 to 1100 JST. (b) Displacement of echoes progressing from the ranges of 270° to 280°. (c) Same as (b) for the ranges of 280° to 300°. (d) Same as (b) for the ranges more than 300°.

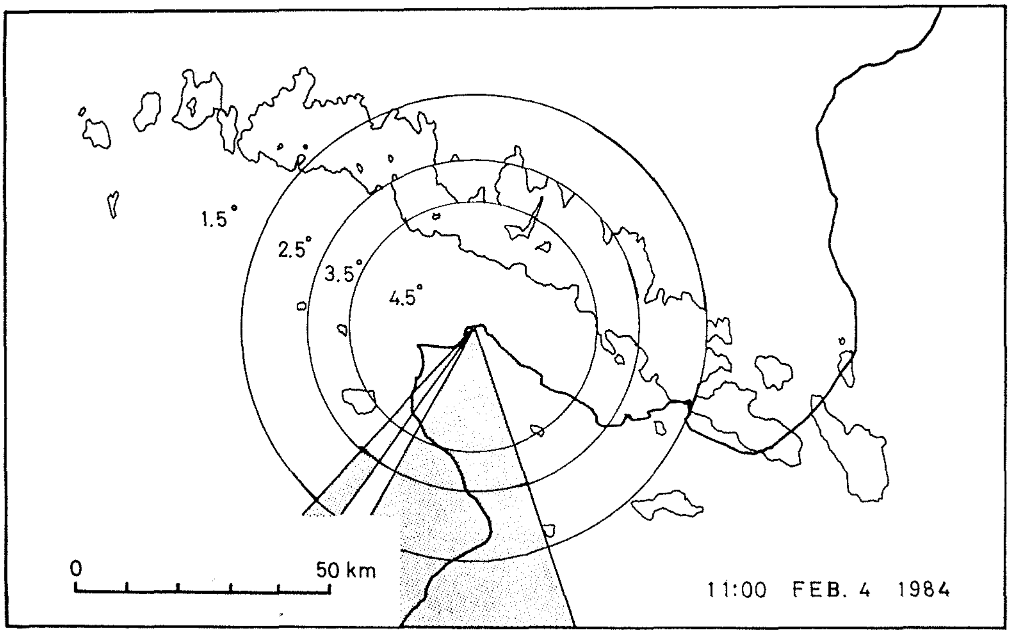


Figure 11. CAPPI echo pattern at 2 km above sea level. 1100 JST Feb. 4, 1984.

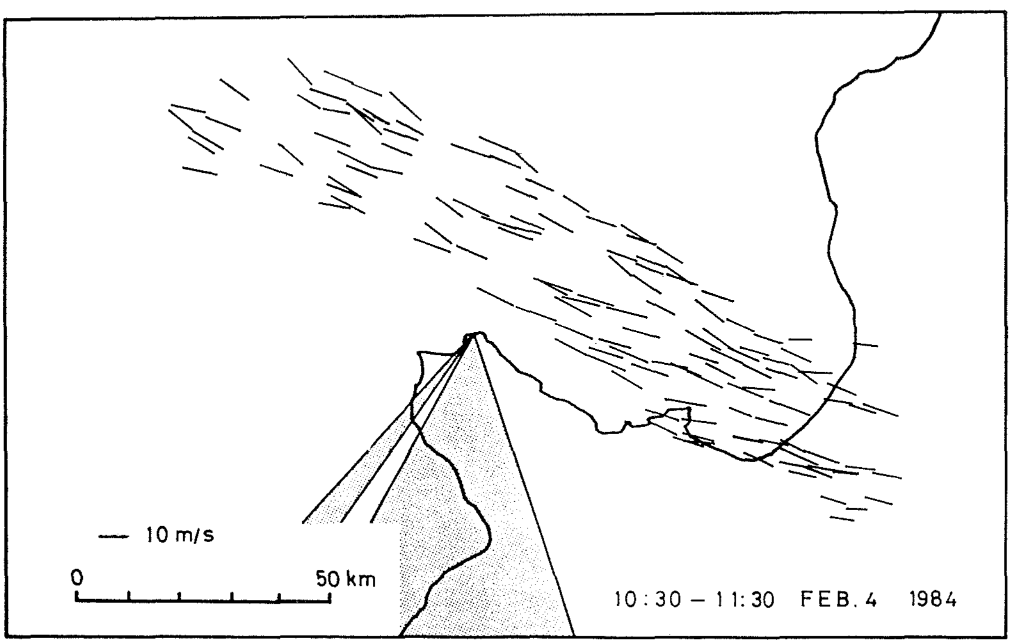


Figure 12. Displacement of CAPPI echo patterns at 2 km at 10 min. intervals from 1030 to 1130 JST Feb. 4, 1984.

103° around the Point Takashima, and from 289° to 109° over the Ishikari Plain. It is apparent therefore that the direction of movement of precipitation echoes had an additional eastward component of about 10° around the Point Takashima comparing with those in center of the Ishikari Bay. Figure 11 shows a CAPPI echo pattern at 2 km above the sea level made from the composition of PPI echo patterns obtained by different elevation angles from 1.5° to 4.5° at 11 : 00 JST. In this figure the shaded sector shows the area obscured by the mountains. The directions and velocities at each 10 minute intervals of precipitation echoes obtained by the CAPPI at 2 km above the sea level are displayed in Figure 12. As seen in this figure, the directions of the echoes were approximately 295° at the center of the Ishikari Bay and 280° on the eastside of the Point Takashima. A similar tendency was obtained in the case of northwesterly wind.

From the observation results described above, it was shown that when the wind system on the west coast of Hokkaido Island was nearly constant as in a typical winter monsoon, then the direction of movement of the precipitation echoes from snow clouds depended upon the locations where the echoes presented. One particular clear point is that the direction of movement of the precipitation echoes from snow clouds invading from northwest to southeast has a tendency to shift towards the east, by about 10° near the Point Takashima, Otaru and Yoichi close to the inland mountainous regions, compared with the direction of movement of the echoes over the center of the Ishikari Bay. Furthermore, it is suggested that the precipitation echoes in the west sides of the Shakotan Peninsula and the Mashike mountain ranges have a tendency to shift towards the south. From these results it appears that the mountainous topographies forming from Mt. Yoichi (1488 m), Mt. Muine (1461 m) and other mountains located in the southside of Otaru, from Mt. Yobetsu (1298 m), Mt. Shakotan (1255 m) and other mountains located on the westside of Shakotan Peninsula, and the Mashike mountain ranges composing from Mt. Shokambetsu (1491 m), Mt. Hamamasu (1258 m) and other mountains act mainly as a barrier to the monsoon wind. It was expected especially that in the vicinity of Otaru and Yoichi the mountainous topography located in the southside of the Ishikari Bay and the continuous mountain ranges connecting from this topography to the point of the Shakotan Peninsula resulted in a change in the wind system toward the east.

3. Numerical experiments

As described previously, it appears that the direction of movement of precipitation echoes from snow clouds was affected by the mountainous topography around the Shakotan Peninsula located to the west of the Ishikari Plain. To estimate the mountainous topographical effects around the peninsula, we ran numerical experiments using Lavoie's mesoscale model (1972).

a. Lavoie's mesoscale numerical model

The model was developed in order to study "Lake Effect Snow Storms" of

Lake Erie, the Great Lakes, U. S. A., during cold-air outbreaks in the mid-winter seasons. This model simulates the mesoscale disturbance of a well-mixed layer induced in cold-air moving over unfrozen lakes or a warm sea surface. There is a similarity to the process of modification of the atmosphere between Lake Erie and the Japan Sea during the winter monsoon seasons. Estoque and Ninomiya (1976) applied the Lavoie's model to the Japan Sea to simulate the snowfalls along the coast line of the Japan Sea and they showed that the simulated distributions of snowfalls agreed with the observational results. Therefore, we followed their model. That is, the horizontal wind vector (V), potential temperature (θ), mixing ratio (q), and depth of the well-mixed layer (h) are obtained with the aid of prediction equations. And the vertical velocity (w) and precipitation rate (M) are calculated with the aid of the diagnostic equations.

b. Application to circumference of the Ishikari Bay

The Lavoie's model was applied to a 2000 point grid mesh centered on the Ishikari Bay, Hokkaido Island using a 5 km $\times$ 5 km grid around Ishikari Bay and the Shakotan Peninsula, and further exponentially increasing grid distances were used away from this region of prime interest so as to effectively isolate the domain boundaries. Figure 13 shows the calculation domain with the central rectangle being the fine mesh region. Figure 14 shows the averaged topography used in the experiments. The following parameters were used in all experiments. The height

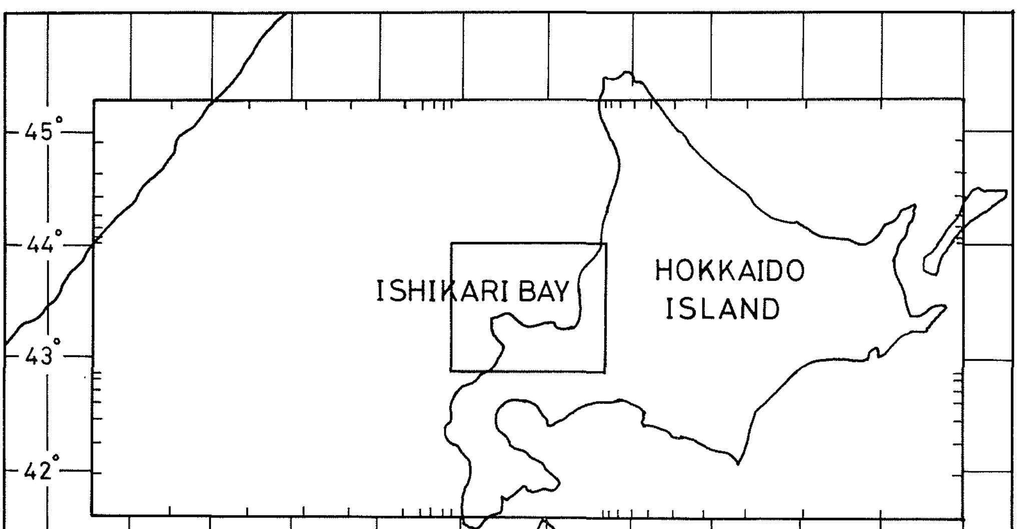


Figure 13. Calculation domain indicated by large rectangle. Inner rectangle is fine mesh region ($\Delta x = \Delta y = 5$ km),

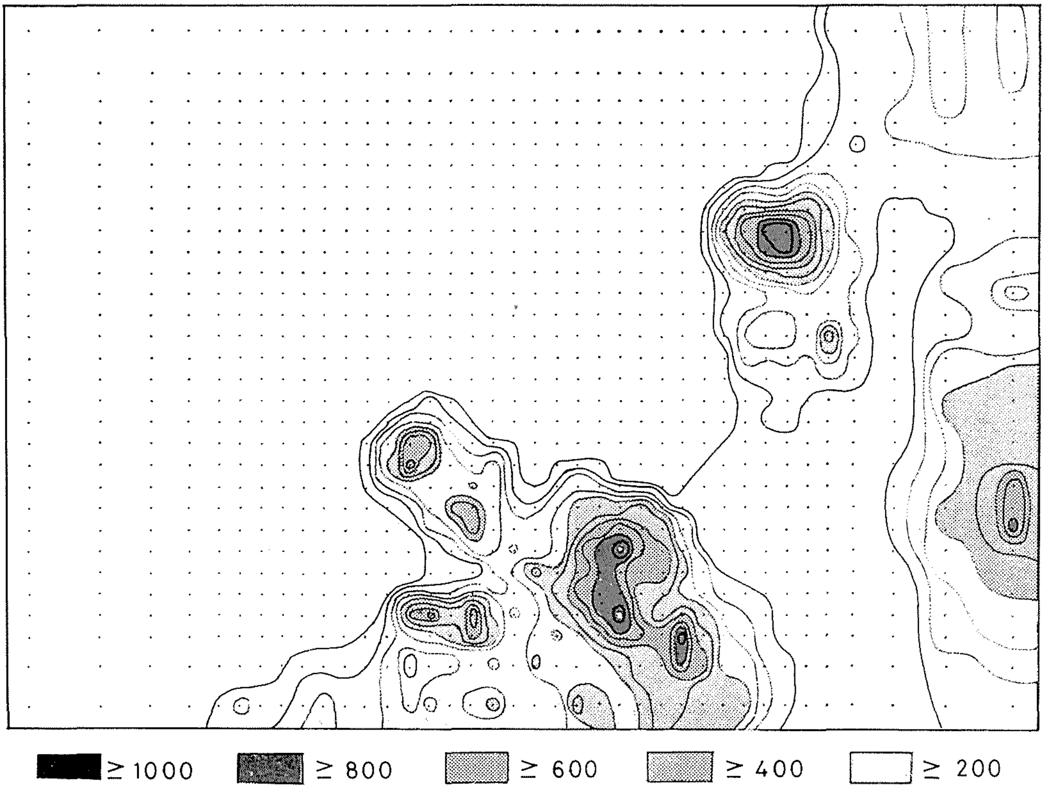


Figure 14. Outline of the Ishikari Bay including fine mesh and distribution of smoothed topography used in calculations. Difference of darkness indicates altitudes in (m).

of bottom of the mixed layer; $Zs = Zo + 5 \times 10^3$ cm, where, Zo is the altitude above sea level; the drag coefficient of momentum, C_D is 7.0×10^{-3} at the ground surface and 1.5×10^{-3} at the sea surface; the drag coefficient of heat, C'_D is 1.5×10^{-3} when θ is smaller than θ_0 and zero when θ is larger than or equal to θ_0, where θ and θ_0 are potential temperatures at the mixed layer and at the surface, respectively; the Coriolis' parameter; $f = 1.0 \times 10^{-4}\,\mathrm{sec}^{-1}$ at 43.5° in latitude north.

To estimate the topographic effect, the experiments were carried out for six cases as shown in Table 1. In this table, the experiment No. 1 corresponds to the condition of February 4, 1984 with an imposed topography, and No. 2 is the similar condition of No. 1 with no topography, that is to say, flat surface. In the third experiment, the initial condition of wind direction, and in the fifth experiment, the initial condition of height of top of the mixed layer were changed. The experiments No. 4 and No. 6 are the similar conditions of No. 3 and No. 5 except that topography is removed and a flat surfaces used. Figure 15 shows the vertical profile of air temperature at Sapporo on 21:00 JST Feb. 3, 1984 as a solid line, and for 09:00 Feb. 4, 1984 as a dotted line. As seen in the figure, the heights of bottom of the inversion layer were 2,911 m on 21:00 Feb. 3, and 3,618 m on

Table 1. Characteristics of the numerical experiments

Exp. No.	Initial wind speed (m/sec)	Initial wind direction	Topography	Initial inversion height (m)
1	12.0	315.0°NW	imposed	3000
2	12.0	315.0°NW	flat	3000
3	12.0	337.5°NNW	imposed	3000
4	12.0	337.5°NNW	flat	3000
5	12.0	315.0°NW	imposed	2000
6	12.0	315.0°NW	flat	2000

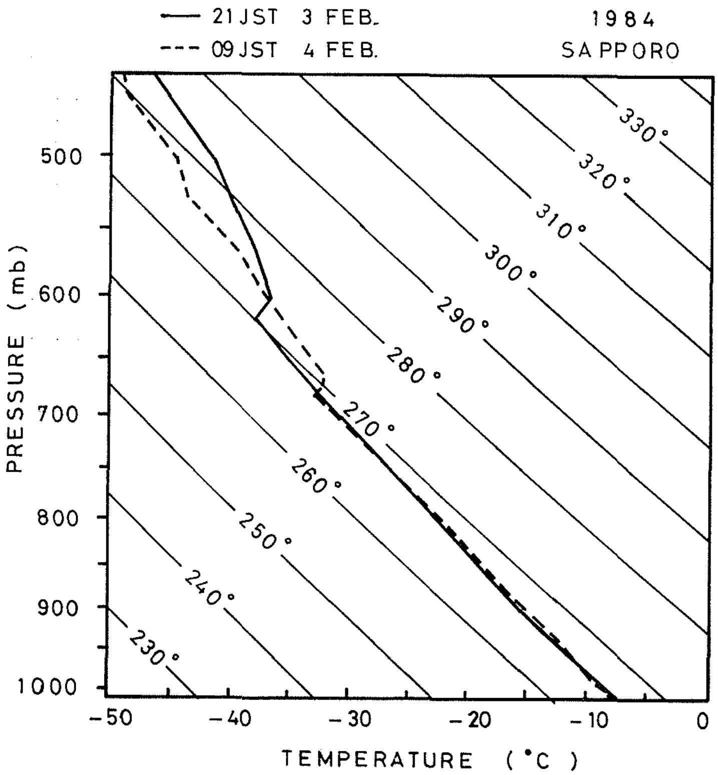


Figure 15. Temperature profiles at Sapporo, 2100 JST Feb. 3 (solid line) and 0900 JST Feb. 4 (dashed line), 1984.

09 : 00 Feb. 4. The average potential temperatures in the mixed layer were 267.1 K and 267.2 K, and the temperature lapse rates were 8.59°C$\cdot$km^{-1} and 8.40°C$\cdot$km^{-1} respectively. On the other hand, the vertical wind profile on 09 : 00 Feb. 4, 1984 is shown in Figure 16, the average wind direction and wind speed in the mixed layer being 305° and 12.0 m$\cdot$sec^{-1}, respectively. Furthermore, the average surface water temperature distribution in early February 1984 was used as the sea surface temperature in the experiments as shown in Figure 17. For the meteorological parameters described above, the experiments were carried out under the following

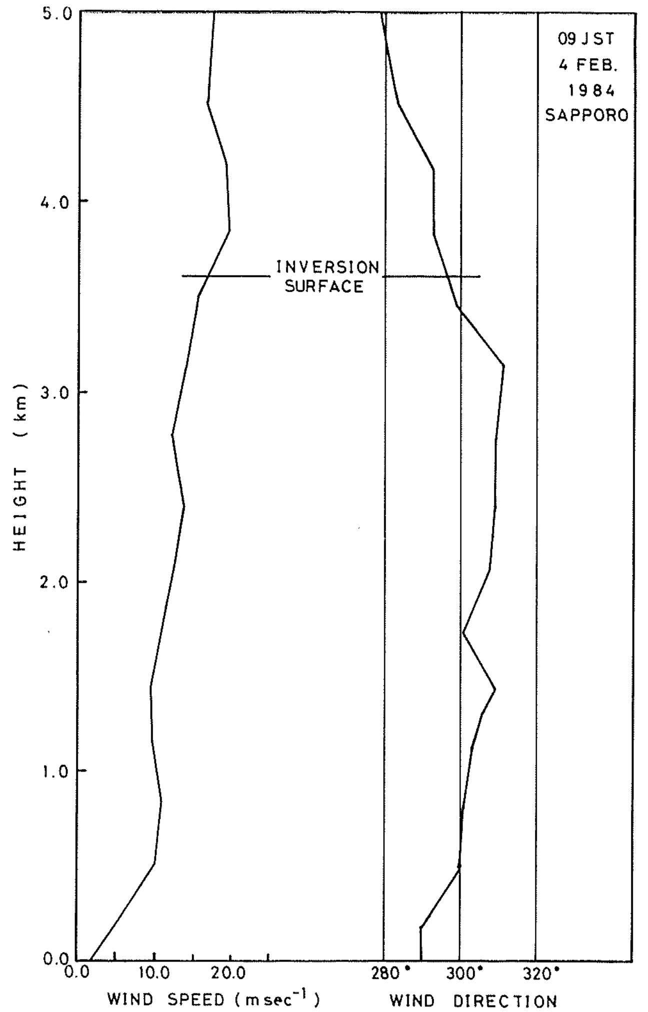


Figure 16. Vertical profiles of wind speed (left) and wind direction (right) at Sapporo, 0900 JST Feb. 4, 1984.

initial conditions: Wind direction, 315°; Wind speed, 12.0 $m \cdot sec^{-1}$; Potential temperature on the ground surface 267.0 K; Potential temperature in the atmosphere, 267.0 K; Strength of inversion, 2 K; Potential temperature gradient in the stable layer, 5.86 $K \cdot km^{-1}$; Vertical wind shear over the mixed layer, 315° and 8 $m \cdot sec^{-1} \cdot km^{-1}$; Height of top of the mixed layer, 3000 m; Mixing ratio in the mixed layer, 0.6 $gm \cdot kg^{-1}$; Mixing ratio in the stable layer, 0.3 $gm \cdot kg^{-1}$. The other model parameters were in accordance with the values used by Lavoie.

c. Experiment results

It appears that the direction of movement of the precipitation echoes depends mainly on the wind system in which the precipitation echoes exist. The numerical experiments were made on the wind system in the mixed layer, change of inversion

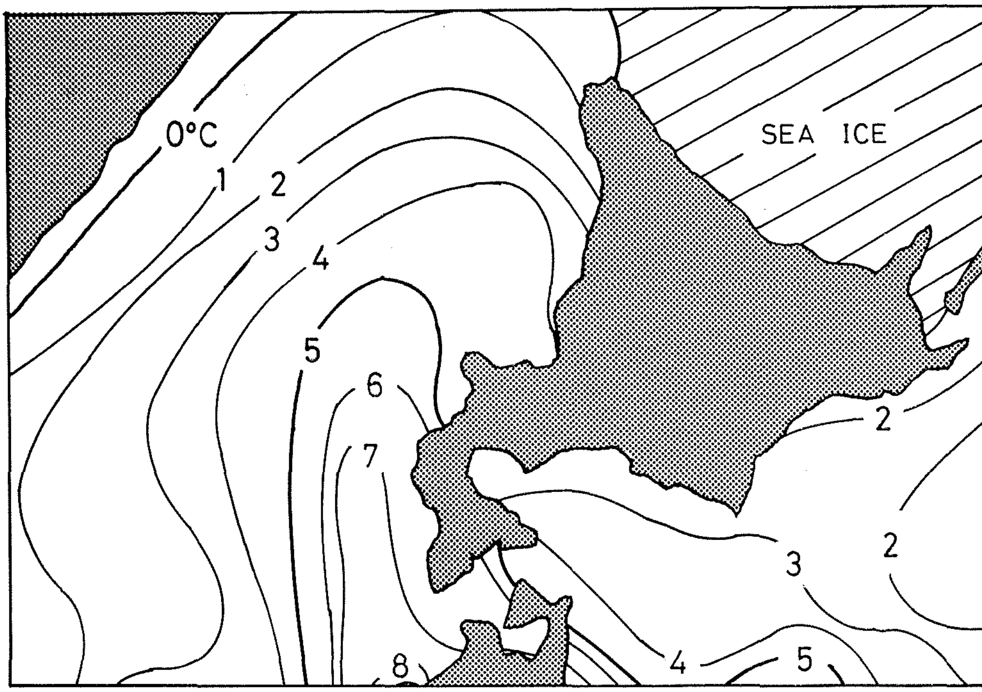
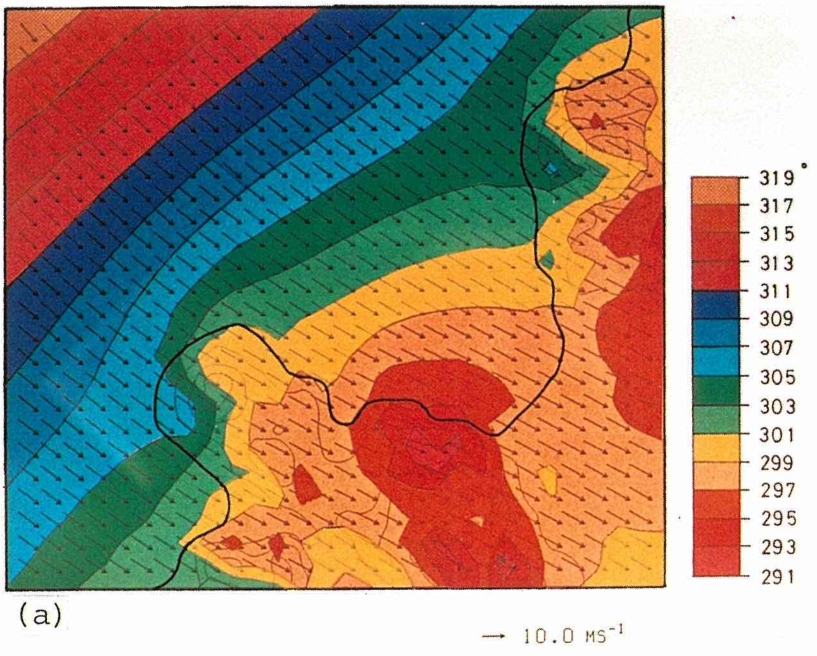


Figure 17. Average sea surface temperature distribution in the early February 1984.

height of the mixed layer, divergence field, and precipitation fields and so on. In this paper, however, the principal object was placed on the wind systems in the mixed layers. In addition, the wind systems in the mixed layers with and without topographical influences were compared.

Figure 18 (a) and (b) shows the horizontal distributions of wind direction in the mixed layer for experiment Nos. 1 and 2, that is a 315°, northwest wind in Table 1. Contours show the isogons of wind direction every 2 degrees. As the roughness on the sea and ground surfaces is considered, respectively, the wind direction shifts because of the frictional influences relatively eastwards in a general tendency from the initial condition of 315°. As seen in the Figure 18 (a), however, the wind direction shifts eastwards more near the Point Takashima (291.6°) to the west of the plain as compared to the mean wind direction in the center of the Ishikari Bay (304°) when topography is included. The difference between wind directions in both locations is by 10 degrees or more. Further, at the southwest side of the Shakotan Peninsula, the wind direction is more southerly as compared with the northeast side of the peninsula. This tendency was seen in the southwest side of the Shokambetsu mountainous regions. On the other hand, in the case without topography, the wind direction was homogeneous as shown in Figure 18 (b). Comparison of Figure 18 (a) and (b) demonstrates that the topography of the Shakotan Peninsula influences wind direction in the mixed layer. Figure 19 shows the horizontal distribution of the deviation from the initial inversion height (3000 m). The



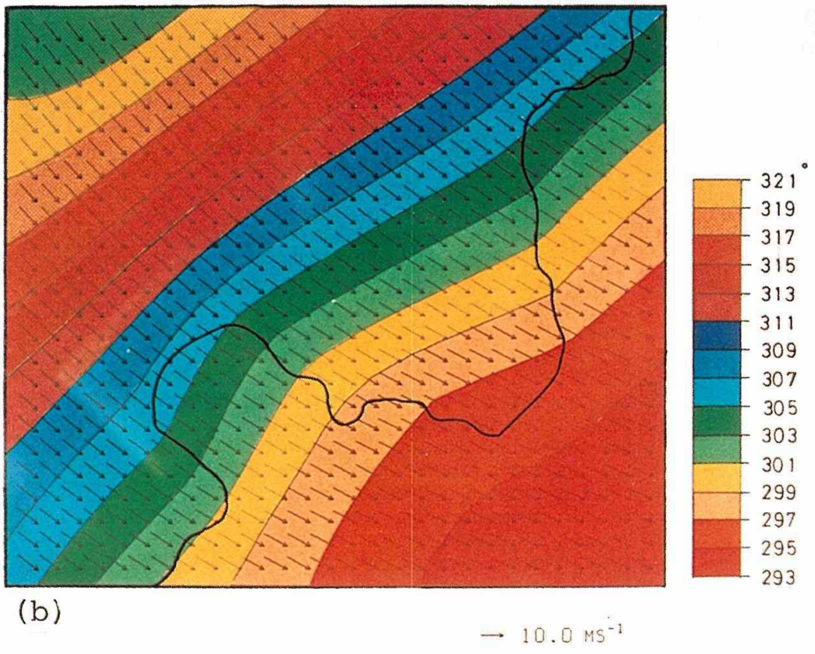


Figure 18. The horizontal distribution of the mean wind direction and speed in the mixed layer. Solid line shows the coast line and thin lines show the contours of 200 m interval of topography.
(a) Experiment No. 1. (b) Experiment No. 2.

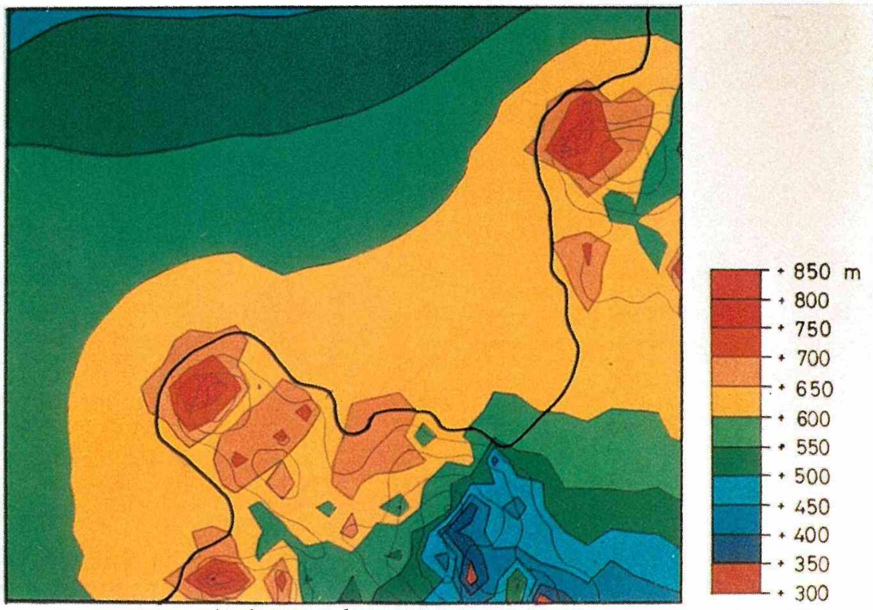


Figure 19. The horizontal distribution of the deviation from the initial inversion height in the experiment No. 1.

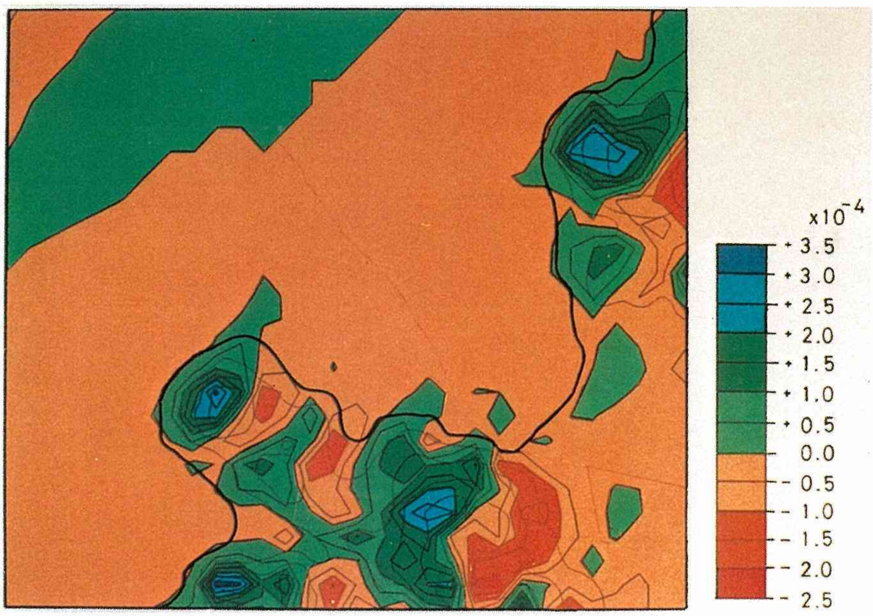


Figure 20. The horizontal distribution of the divergence field in the experiment No. 1.

deviation increases very gradually from the Japan Sea to the coast line of the Ishikari Bay, showing that the mixed layer is developing gradually. Contrary to this, at the upwind sides of the Shakotan Peninsula and Shokambetsu mountainous regions located northward the Ishikari Plain, it rises rapidly by 800 m or more. It is believed that the rapid increase of the mixed layer is brought on by the forced updraft caused by the topography. On the other hand, the deviation diminishes as it advances inland to the plain. It appears therefore that there are only heat and vapor supplies over the plain. Figure 20 shows the divergence field in the stable condition of the experiment No. 1. It is clearly seen in the figure that there are strong divergence and convergence fields in the upwind and leewind sides of the mountainous regions described previously. This tendency corresponds to a wind direction caused by deflecting by the mountainous regions. In the case of experiment Nos. 3 and 4, that is 337.5°, north-northwest wind, similar results were obtained in the shift of wind direction, the deviation from the initial inversion height, and the divergence field as described in the experiment Nos. 1 and 2. Furthermore, in the case of experiment Nos. 5 and 6, where the initial inversion height was 2000 m, similar results were obtained for all factors. However, the wind direction as a general tendency shifts eastwards more than in the experiment No. 1. In the deviation from the initial height, the maximum value was found on the upwind side of the Shokambetsu mountainous regions. The grid point having maximum value obtained in the experiment No. 5 showed the second highest value in the experiment No. 1 and the maximum value in the experiment No. 3. Comparing with the initial values at the grid point, it changed by 28.6% in the No. 1, 23.5% in the No. 2, and 34.1% in the experiment No. 5. It is concluded that these numerical results in which the initial inversion height is 2000 m, indicate that the thinner the depth of the mixed layer, the larger the topographic effects. Further, in the divergence field, the maximum values of divergence and convergence were larger than those of the experiment No. 1.

The numerical experiments demonstrated therefore that the wind direction shifts eastwards by about 10 degrees near the Point Takashima to the west of the Ishikari Plain as compared to the mean wind direction in the center of the Ishikari Bay when topography is included. This tendency was shown in the cases of wind directions of northwest and/or north-northwest. It was also shown that the wind goes round the mountainous regions. These results had a close correspondence to the movement of precipitating snow clouds obtained by our radar observations described earlier. From the comparison with the cases with and without topography, we concluded that the results obtained above depended upon the topographic effect. In addition the experiments for different inversion heights indicate that the thinner the depth of mixed layer, the larger the topographic effects.

4. Concluding remarks

The radar observations carried out at the Shakotan Peninsula indicated that the direction of movement of the echoes from the precipitating snow clouds invading from the northwest to the southeast had a tendency to shift towards the east, by about 10 degrees near the mountainous regions, when compared the echoes over the center of the Ishikari Bay. This tendency was the same for echoes from the north-northwest to the south-southeast. It appears therefore that the tendency seemed to reflect the influence of the mountainous regions. The numerical experiments indicate also that the wind direction in a mixed layer shifted eastwards by about 10 degrees near the mountainous regions to the west of the Ishikari Plain as compared to that in the center of the Ishikari Bay. Considering the fact that radar echoes of precipitating snow clouds moves along the mean wind direction in the mixed layer, this result agrees well with that obtained by the radar observations. It is expected that the results obtained by this study will provide valuable information for the nowcasting of snowfalls in the Ishikari Plain (Asuma et al., 1984).

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