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A Case Study of Heavy Rainfalls from the Shallow Orographic Precipitating Clouds in the Orofure Mountain Range, Hokkaido, Japan

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Abstract

To study the mechanism of orographic rainfalls, observations using a mobile weather radar, raingauges and wind vanes and anemometers on the southeastern slope of the Orofure mountain range, Iburi Sub-prefecture, Hokkaido, Japan were carried out from late August to early September in 1985 and 1986. In the rainfall from 29 to 30 August 1985, the horizontal distribution of total rainfall amount showed two maximum peaks in the mountainous region and on the seaside region parallel to the coastline around Noboribetsu City. It was considered that the former was caused by the continuous rainfall from the very shallow and weak precipitating clouds maintained by the horizontal convergence of the wet air flow close to the ground surface, and the latter was caused by the showery rainfall from the shallow convective precipitating clouds whose echo top was lower than 3 km above sea level. And the shallow precipitating cloud over the seaside region was considered to be the result of the uplifting of the wet southeasterly wind in the lower layer from the Pacific Ocean on the southeastern slope of the mountain range near the coastline. Further it was difficult to expect the occurrence of such a heavy rainfall, because the depression on which our attention was focused as one of causes of the heavy rainfall on this region did not exist over the Sea of Japan to the offshore of Akita Prefecture. The southeasterly wind in the lower layer was caused by the outbreak from the high pressure over the Sea of Okhotsk in this case.

1. Introduction

It is well known that the southeastern slope of the Orofure mountain range in the Iburi Sub-prefecture of Hokkaido has abundant rainfalls. And heavy rainfalls amounting to more than 90 mm/day occur 3 or 4 times per year in this region (Takeda and Kikuchi, 1978). Kikuchi and his group have studied the heavy rainfalls in this region for about 10 years. Konno and Kikuchi (1981) classified the horizontal distribution patterns of rainfall amount into five types

based on the result of observations using their special mesoscale raingauge network. And they clarified that the distribution patterns were mainly influenced by the wind direction in the lower layer. Especially, the 'Orographic rainfall', in which the maximum peak of the rainfall amount was situated in the mountainous region of the southeastern slope of the range, occurred when the wind direction of the lower layer was southeasterly. Furthermore, Konno et al. (1981) made the observations on the size distribution of raindrops at two observation sites on the mountain range and on the seaside. The result of their observations suggested that the heavy orographic rainfalls in this range arose from a combination of the lower layer clouds caused by uplifting of the warm wet air from the Pacific Ocean and the precipitation from the upper level clouds of the synoptic scale disturbance moving from the southwest to the northeast over this region. The numerical experiments by Konno and Kikuchi (1981) and Kikuchi et al. (1988) supported this conclusion, and they pointed out the importance of the effect of the horizontal convergence of the warm wet air flow near the ground surface along the valleys. Iwanami et al. (1988) clarified the enhancement of rainfall amount by the two-layer cloud structure through their radar observation.

The studies on the orographic rainfalls have developed in South Wales in United Kingdom. Browning et al. (1974) suggested the importance of the existence of the potential instability in the middle troposphere, and Hill et al. (1981) emphasized the importance of the interaction between raindrops from the upper level clouds and small droplets within the low level clouds from the results of the observation using radars, radiosondes and raingauges.

Our radar observations were carried out at Orofure mountain range from late August to early September in 1985 and 1986, in combination with raingauges and wind vanes and anemometers that were set up there for the first time. In this paper, a case study about the heavy rainfall from the shallow orographic precipitating cloud from 29 to 30 August in 1985 will be described.

2. Observation area

Figure 1 shows the observation area. The southeastern slope of the Orofure mountain range faces the Pacific Ocean from Tomakomai (B-71) to Shiraoui (S-11), Noboribetsu (A-57) and Muroran (B-77), thus the orographic rainfalls caused by the uplifting of the warm and wet southeasterly flow from the Pacific Ocean occur frequently on the mountain range. In the figure, the symbols of ○, ⊗ and ● represent the locations of the meteorological observa-

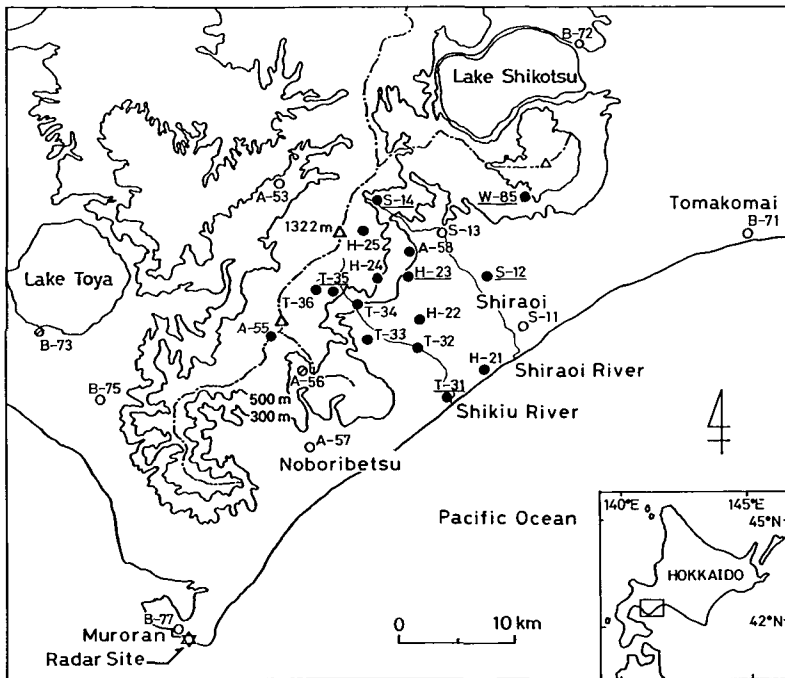


Fig. 1 Map of the observation area. Symbols ○ : Meteorological observatory and AMeDAS supported by JMA, ⊙ : Rainfall amount measuring robot supported by JMA, ● : rain gauge supported by this work. Wind vanes and anemometers were set up at the sites underlined.

tories or AMeDAS, the rainfall amount measuring robots of Japan Meteorological Agency (JMA), and our 14 rain gauge sites, respectively. Further we set up 6 wind vanes and anemometers at the sites underlined. This observation network includes two valleys, that is, the S-line along the Shiraoui River from Shiraoui (S-11) to the Shiraoui waterfall (S-14) and T-line along the Shikiu River from Takeura (T-31) to close to the watershed of Kushibetsu (T-36). The H-line from Hagino (H-21) to near Todomatsuzawa (H-25) was located on the ridge between the two lines described above. A-53 site is located on the northwestern slope of the Orofure mountain range.

Our mobile weather radar was set up on the hill on the southeast side of Muroran City in order to watch the southeastern slope of the Orofure mountain range.

3. Results

Figure 2 shows the surface weather chart at 09 JST on August 30, 1985. Up till the present, the depression staying on the Sea of Japan to the offshore of Akita Prefecture and the southeasterly wind blowing into this depression have been mainly watched as the synoptic situation that caused heavy rainfalls in this region. In this case, however, no depression existed over the Sea of Japan, and the southerly wind in the lower layer shown in Fig. 3 was caused by the outbreak from the high pressure over the Sea of Okhotsk. Thus it was difficult to forecast the occurrence of the heavy rainfall at this time.

Figure 3 shows a time-height cross section of the wind direction and speed above Sapporo from 21 JST on August 28 to 03 JST on August 31 in 1985. The contours of the wind speed are drawn at 5 m/s intervals from 5 m/s, and the areas where relative humidity was higher than 80% and lower than 20% are stippled and meshed, respectively. The southerly wind lower than about 850 mb level became dominant from 21 JST on August 29, and it was caused by the

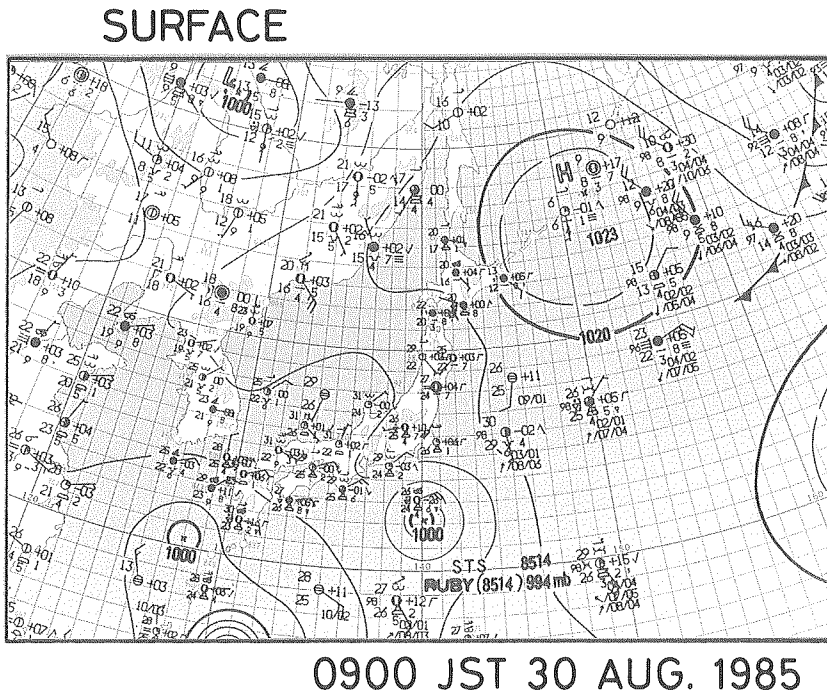


Fig. 2 Surface weather chart at 09 JST on August 30, 1985 (after JMA).

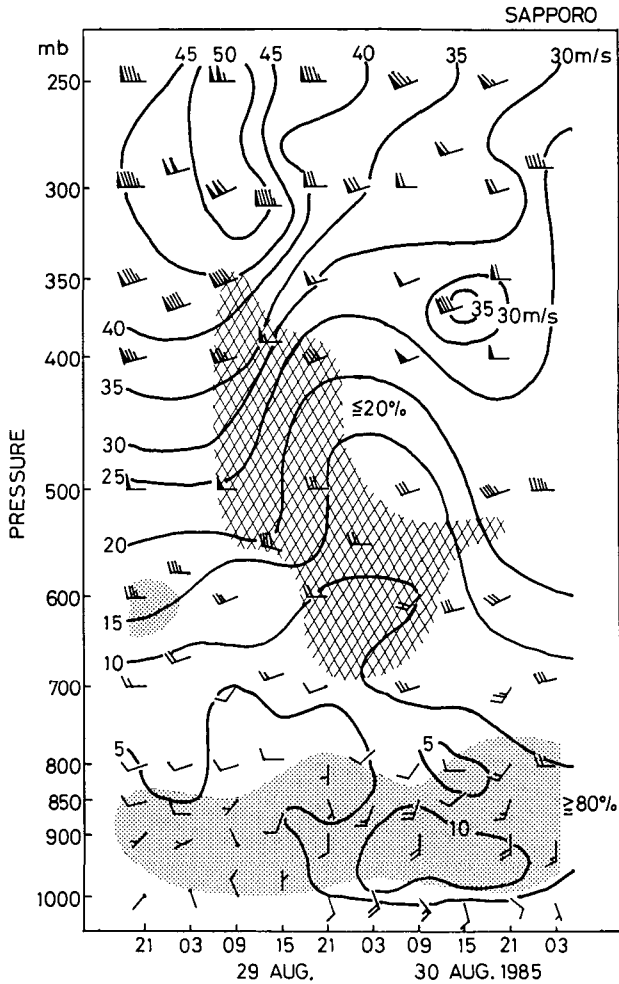


Fig. 3 Time-height cross section of the wind direction and speed at Sapporo.

outbreak from the high pressure over the Sea of Okhotsk shown in Fig. 2. This southerly wind was so humid and it was estimated that the wet southerly wind blew in the lower layer alone over the southeastern slope of the Orofure mountain range located southwards of Sapporo. On the other hand, the very dry air whose relative humidity was lower than 20% existed in the upper layer than 700 mb level, and it was considered that this dry air was one of causes of the shallowness of the precipitating cloud near the coastline discussed subsequently.

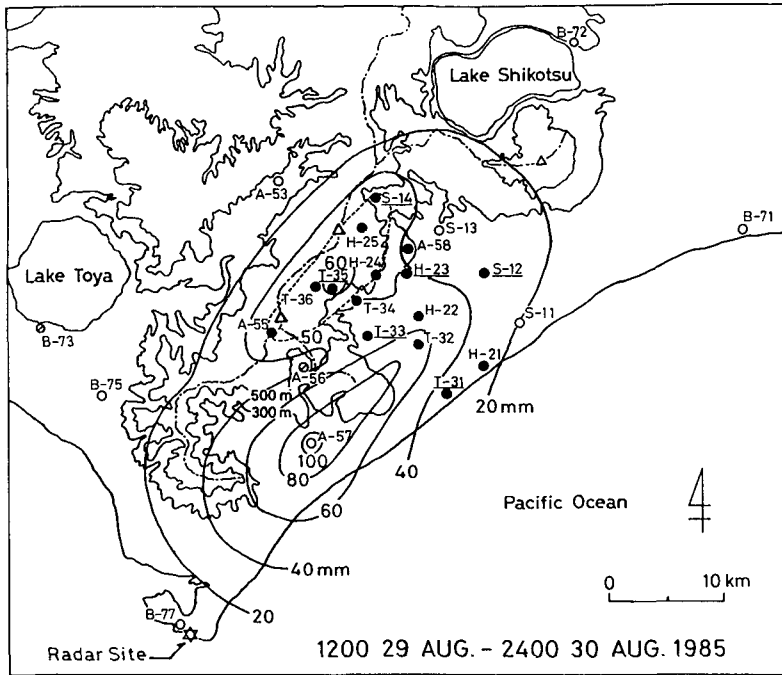


Fig. 4 Horizontal distribution of total rainfall amount.

The horizontal distribution of total rainfall amount for this case is shown in Fig. 4. The contours are drawn at 20 mm intervals from 20 mm. The rainfall amount was distributed mainly on the southeastern slope of the Orofuro mountain range and there were two maximum peaks more than 50 mm. One of them was located in the mountainous region higher than about 500 m above sea level parallel with the watershed, and the T-35 raingauge site recorded 62 mm. The other was located on the seaside region around Noboribetsu City parallel with the coastline, and the A-57 site of the center of this peak recorded 102 mm. The period and mechanism of production of these two peaks were clearly distinguished.

3.1 Rainfall in the mountainous region

Figure 5(a) shows the horizontal distribution of rainfall amount for 12 hrs from 18 JST on August 29 to 06 JST on August 30, 1985. The contours are drawn at 10 mm intervals from 10 mm except for 5 mm contour drawn by the broken line. In this period, it hardly rained on the seaside region and the maximum peak was located in the mountainous region near the S-14, H-25 and

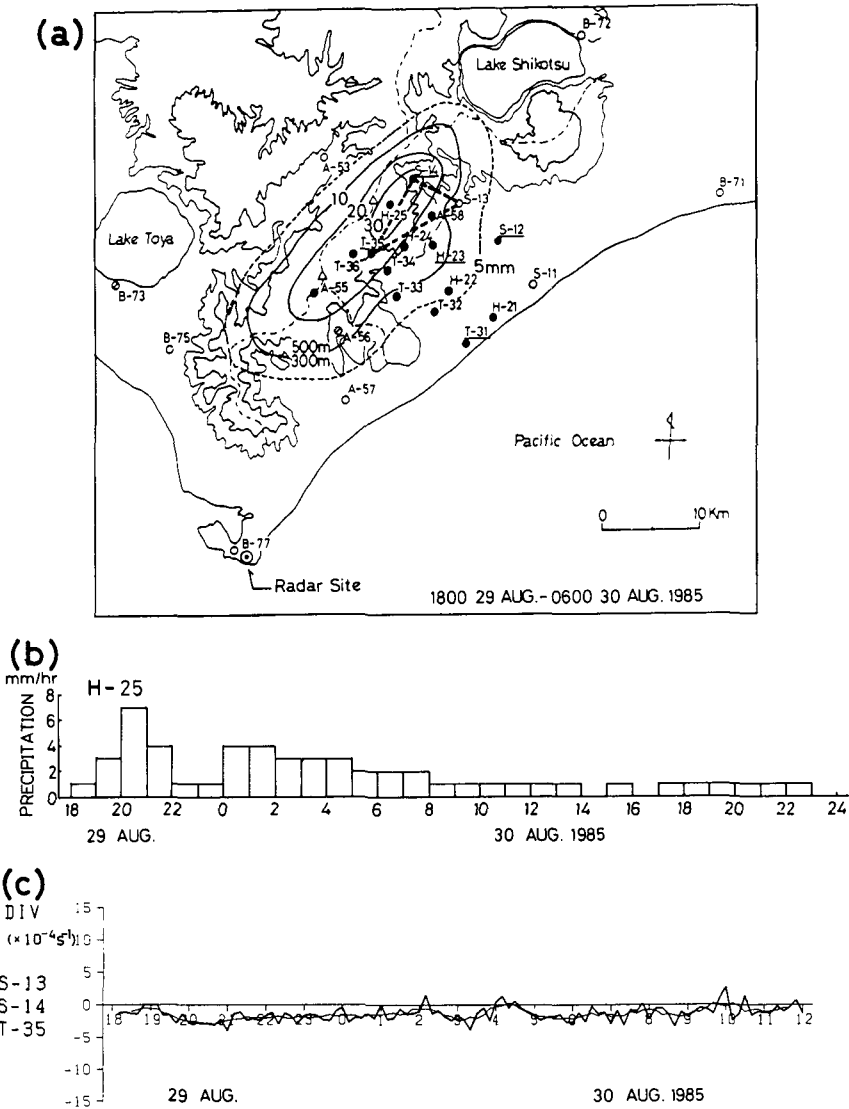
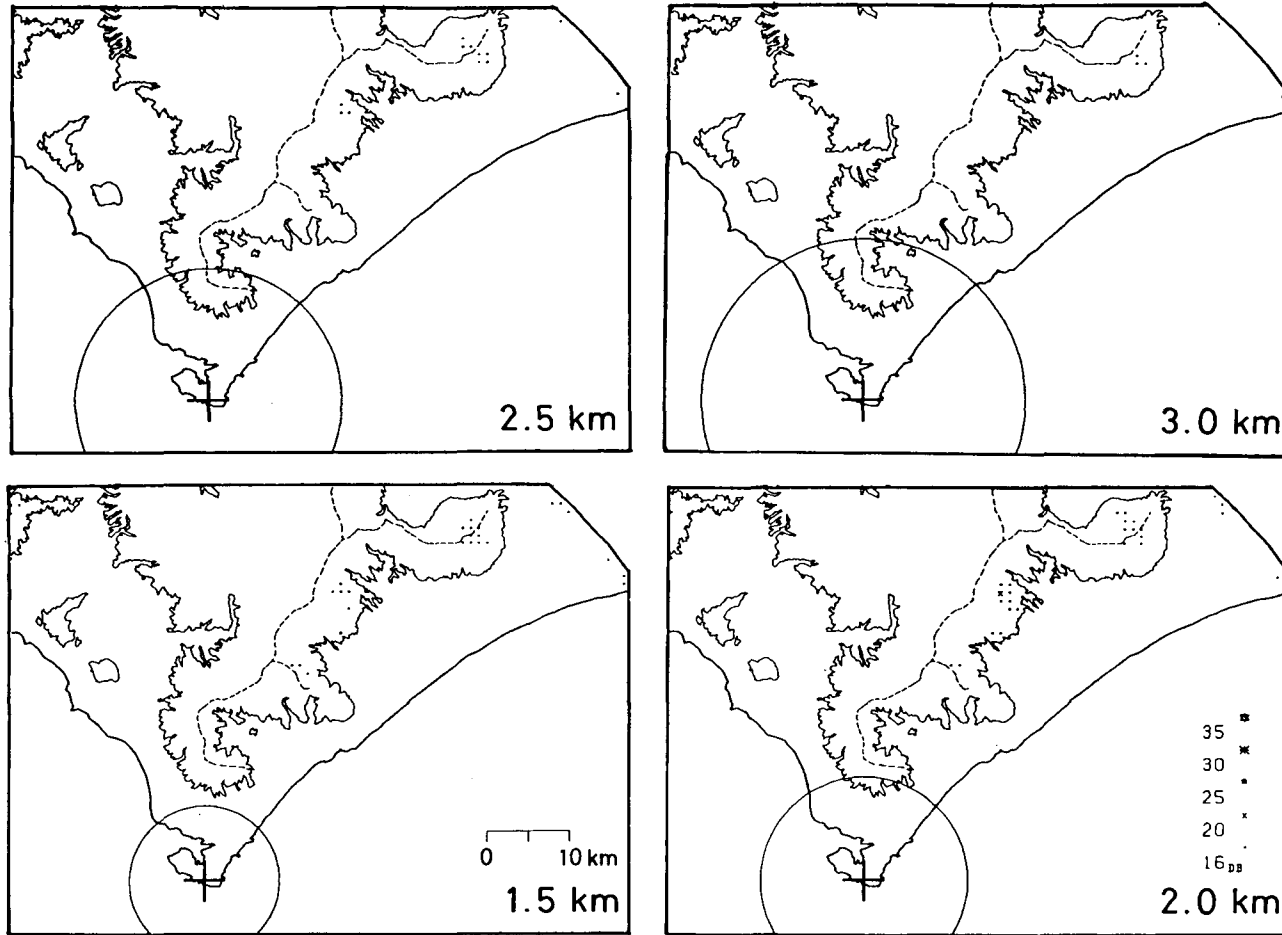


Fig. 5 (a) Horizontal distribution of the rainfall amount from 18 JST on August 29 to 06 JST on August 30, 1985. (b) Time series of the rainfall intensity (mm/hr) at the H-25 rain gauge site. (c) Time evolution of the surface divergence (thick solid line) and 50 min running mean of that (thin solid line) for the triangle area enclosed by the S-13, S-14 and T-35.

CAPPI



2130 - 2134 29 AUG. 1985

Fig. 6 CAPPI pictures of the height of 1.5, 2.0, 2.5 and 3.0 km above sea level.

T-35 raingauge sites along the watershed. The time series of rainfall intensities (mm/hr) at H-25 site that recorded the most rainfall amount of 36 mm in all raingauge sites in this period is shown in Fig. 5(b). Although the peak value was only 7 mm/hr, a weak rain from 1 to 3 mm/hr continued throughout this period at the H-25 site. It was considered therefore that the rainfall amount in this period was not recorded by strong intensity but by long duration of the rainfall.

The time evolution of surface divergence in the triangle area enclosed by the S-13, S-14 and T-35 indicated by thick broken line in Fig. 5(a) in the mountainous region is shown in Fig. 5(c). These surface divergence values were calculated by means of method of Bellamy (1949) using 10 min average values of wind direction and speed, and 50 min running means were also calculated. They are drawn by the thick and thin solid lines in the figure, respectively. Although the value of -2 to $-3 \times 10^{-4} \text{ sec}^{-1}$ was small, the surface divergence continued to be negative in this period. Thus it was considered that the updraft by the convergence of wet air flow continued in the lower layer near the ground surface along the southeastern slope.

Figure 6 shows CAPPI pictures of 1.5, 2.0, 2.5 and 3.0 km above sea level calculated by PPI series from 21:30 to 21:34 JST on August 29, 1985. The echo intensity is shown by symbols indicated on lower right in the 2.0 km CAPPI picture, and the coastline, crestline and contour of 300 m above sea level are drawn by thick solid, thin broken, and thin solid lines, respectively. The echoes weaker than 20 dBZ were observed near the S-14 and H-25 sites over the southeastern slope of the range from 1.5 to 2.5 km above sea level. After that, no echoes were observed over the mountainous region after 09 JST on August 30. It was considered, therefore, that the maximum peak of rainfall amount in the mountainous region resulted from the continuous rainfall from very shallow and weak precipitating clouds near the ground surface, and that the updraft caused by the wet southeasterly wind and their horizontal convergence near the ground maintained these clouds.

3.2 *Rainfall near the coastline*

Figure 7 shows the horizontal distribution of rainfall amount for 12 hrs from 06 to 18 JST on August 30 (Fig. 7(a)), the time series of rainfall intensities at the A-57 which recorded 97 mm for this 12 hr (Fig. 7(b)) and the time evolution of surface divergence in the triangle area enclosed by the T-31, H-23 and A-57 indicated by a thick broken line in Fig. 7(a), respectively. Although a weak rainfall was recorded in the mountainous region, the maximum peak was

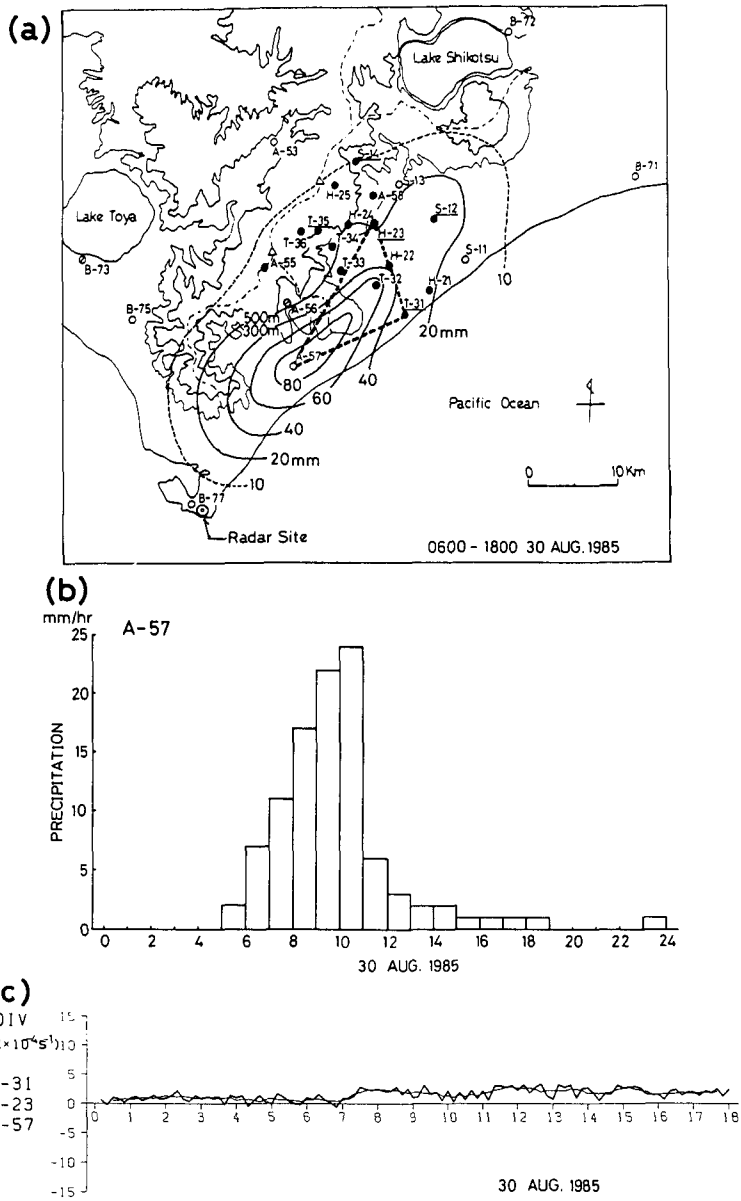


Fig. 7 As in Fig. 5, but for (a) from 06 to 18 JST on August 30, 1985, (b) at the A-57 site, (c) for the triangle area enclosed by the T-31, H-23 and A-57.

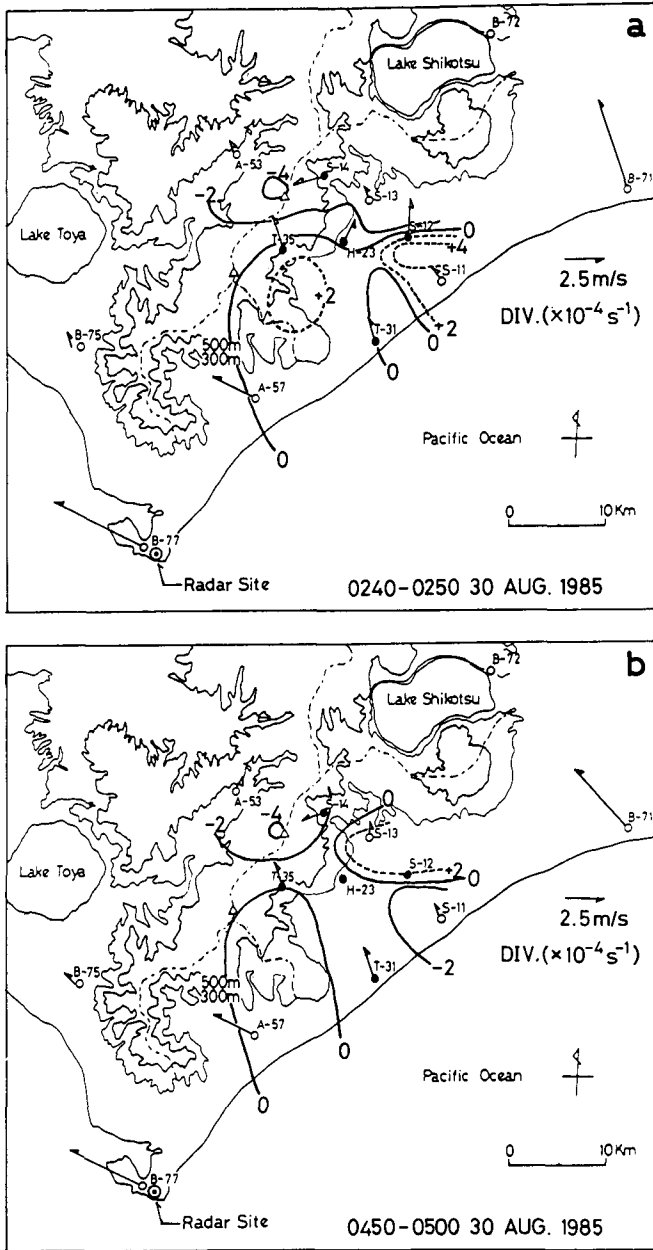


Fig. 8 Wind and divergence field for (a) 02:40-02:50 JST. (b) 04:50-05:00 JST on August 30, 1985.

recorded around the A-57 site in parallel with the coastline in this period (Fig. 7(a)). From Fig. 7(b), the peak value was 24 mm/hr from 10 to 11 JST and the type of rainfall was showery at the A-57 site in contrast with the H-25 as shown previously in Fig. 5(b). Figure 7(c) shows the small divergence value of $+1$ to $+4 \times 10^{-4} \text{ sec}^{-1}$ throughout this period. It is assumed as the cause of this divergence that it rained intensely at the A-57 where the wind data were used to calculate the surface divergence value. As a result, a relatively strong outflow accompanied by intense rainfall was generated. Further, the southerly wind from the Pacific Ocean was divided into easterly and westerly flows by the ridge stretching southeastward between the A-57 and T-31 sites.

Figure 8(a) and (b) show the wind and divergence field for 02 : 40-02 : 50 JST and 04 : 50-05 : 00 JST on August 30, respectively. Winds are indicated by vector of arrows. The contours of surface divergence are drawn at $2 \times 10^{-4} \text{ sec}^{-1}$ intervals, and solid and broken contours indicate negative and positive values, respectively. Figure 8(a) shows the typical distribution when it rained in the mountainous region as discussed in the previous section, and the wide surface convergence area with small value of 0 to $-4 \times 10^{-4} \text{ sec}^{-1}$ extended to the mountainous region. Figure 8(b) shows the distribution just before it began to rain at the A-57 and T-32 sites. Although the surface divergence values near the ridge between the A-57 and T-31 was positive, the surface convergence increased in area and magnitude near the coastline in comparison with Fig. 8(a). Thus it was considered that the surface divergence field also became suitable for rainfall near the coastline.

Figure 9 shows the wind and divergence field superimposed by the CAPPI image at 1.0 km in height. The southeasterly wind blew over the sea judging from the wind at the B-77 in Fig. 9(a). Thus, it was considered that the echo parallel with the coastline was caused by the uplifting of the warm wet air from the Pacific Ocean on the southeastern slope of the mountain range near the coastline around Noboribetsu City. And the southeasterly wind from the sea was divided into easterly and westerly flows by the ridge stretching in a southeasterly direction between A-57 and T-31 judging from the wind direction at the A-57 (east-northeast) and T-31 (west-southwest). And it is considered that these precipitating clouds did not stretch further to the east because of the northerly downward wind on the southeastern slope near the S-line. After 11 : 20 JST, corresponding to the change of wind direction at the T-31 from south-southeast to north, this precipitating cloud moved to south and weakened gradually as shown in Fig. 9(b).

Although this precipitating echoes stayed there for about 3 hrs and recorded

CAPPI (1.0 km)

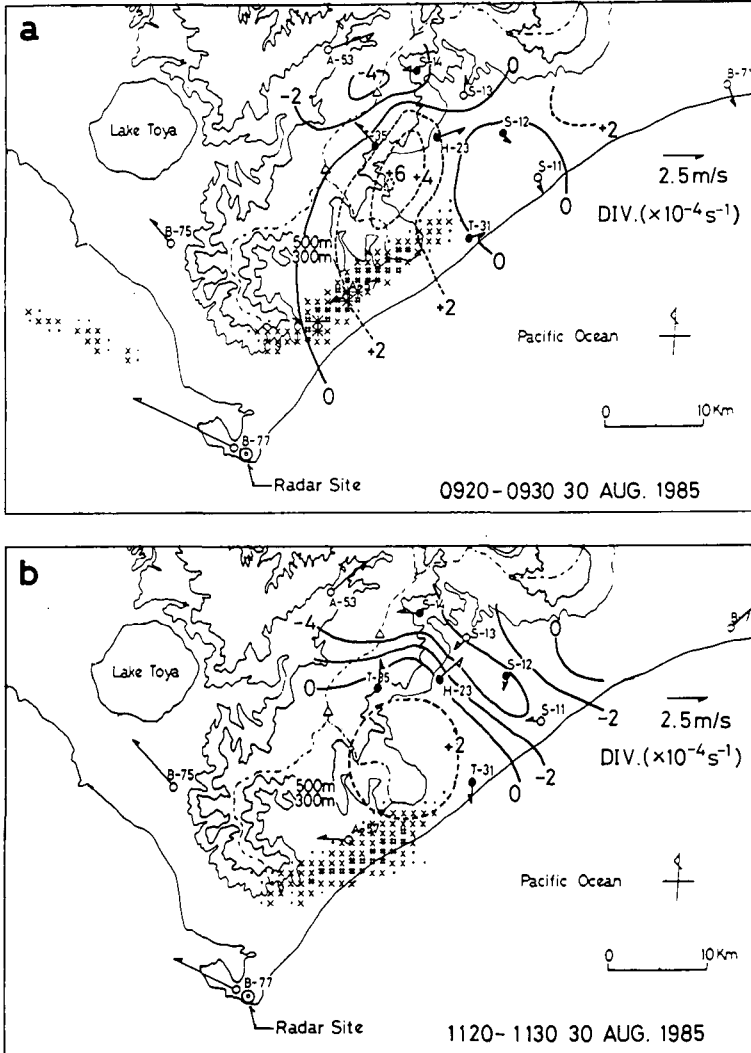


Fig. 9 Wind and divergence field superimposed by 1.0 km CAPPI image for (a) 09:20-09:30 and (b) 11:20-11:30 JST on August 30, 1985.

97 mm for 12 hrs at the A-57, they were shallow convective precipitating clouds. Figure 10 shows CAPPI pictures at 1.0, 2.0, 2.5 and 3.0 km above sea level and vertical cross section, that is, a kind of RHI, along X-X' indicated in the CAPPI picture at 1.0 km calculated from PPI series of the period 09:30-09:36 JST on

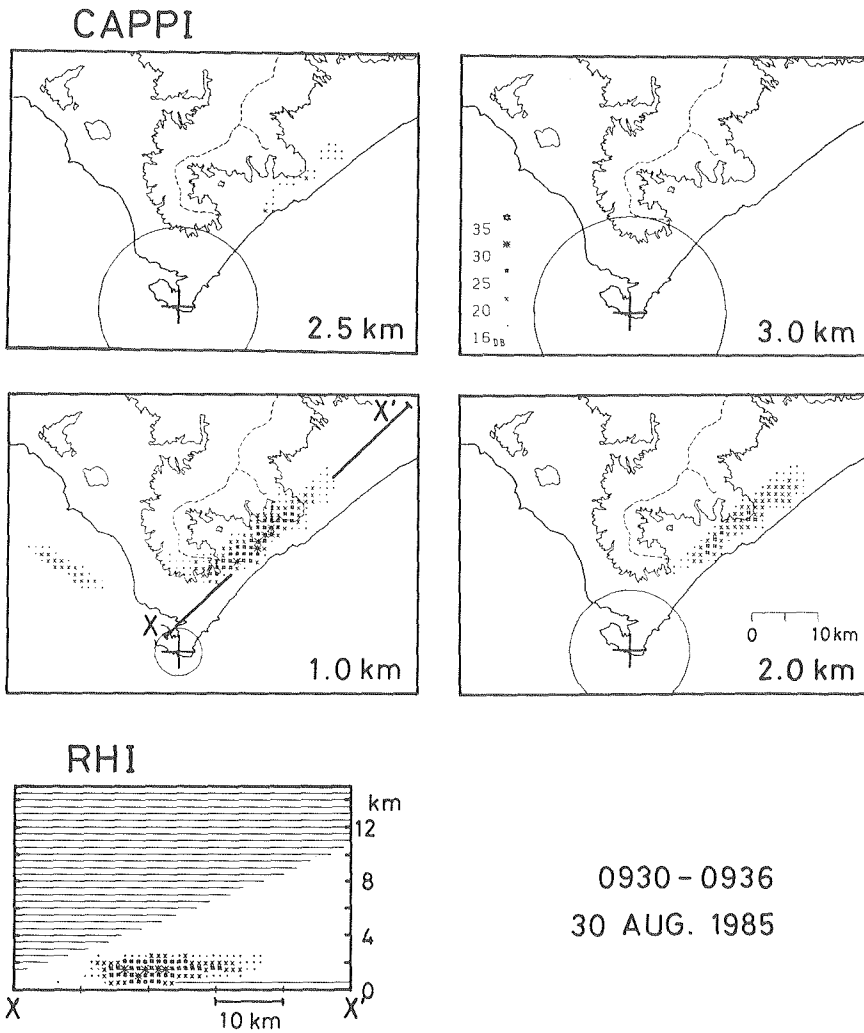
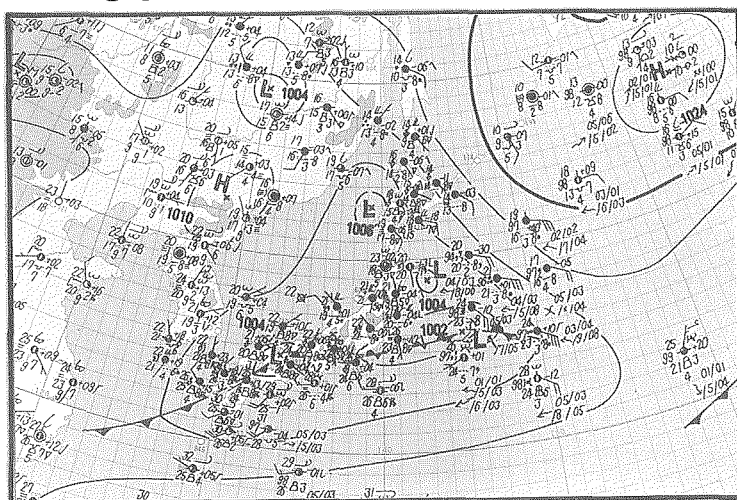


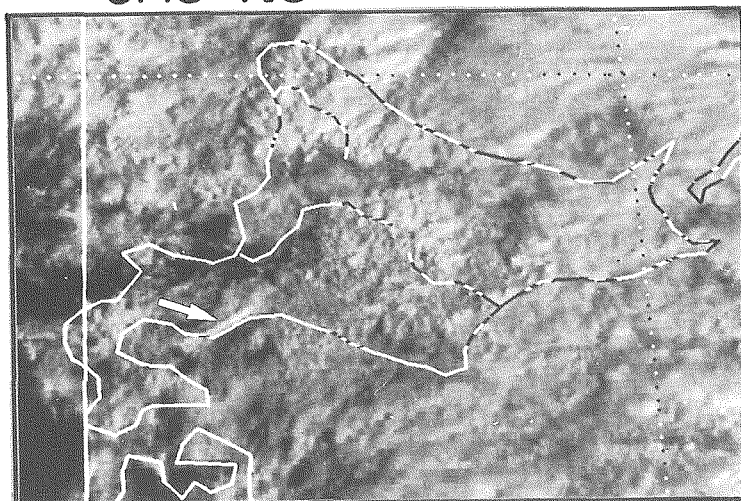
Fig. 10 The CAPPI pictures of the height of 1.0, 2.0, 2.5 and 3.0 km above sea level, and the vertical cross section (RHI) along X-X' drawn in 1.0 km CAPPI picture.

August 30. Judging from the 3.0 km CAPPI and the vertical cross section, the echo top was lower than 3.0 km. As a result, it was considered that the maximum peak of rainfall amount parallel with the coastline around Noboribetsu City was produced by the showery rainfall from the shallow convective precipitating clouds. And the precipitating clouds were caused by the uplifting of the wet southeasterly wind in the lower layer from the Pacific Ocean on the

SURFACE



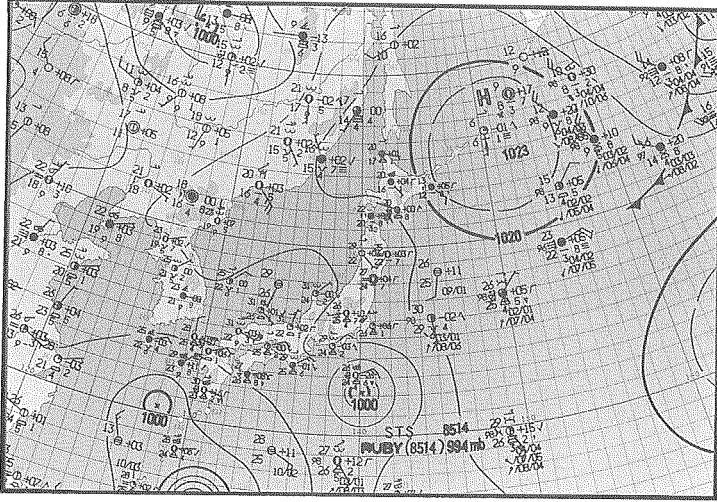
GMS VIS



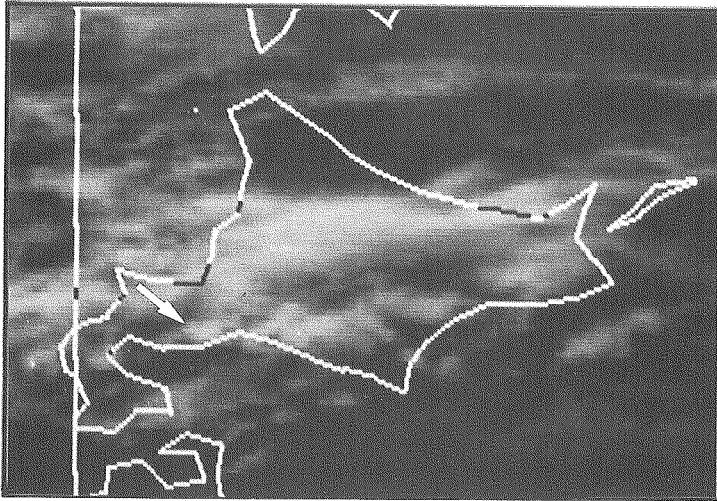
09 JST 31 AUG. 1980

Fig.11 Surface weather chart and visible satellite image of GMS at 09 JST on August 31, 1980 (after JMA).

SURFACE



GMS IR



09 JST 30 AUG. 1985

Fig. 12 Surface weather chart and IR satellite image of GMS at 09 JST on August 30, 1985 (after JMA).

southeastern slope of the mountain range near the coast.

One of the cases of the heavy rainfalls in which the distribution and location of rainfall amount were analogous to this case occurred on August 31, 1980 (Kikuchi et al., 1981). Figure 11 shows the surface weather chart and visible image of GMS at 09 JST on August 31, 1980. In this case, the depression was located on the northern Japan Sea to the west offshore of Hokkaido and the southeasterly wind into this depression blew over the southeastern slope of the Orofure mountain range. And the remarkably clear and long and narrow cloud band as indicated by a white arrow was found over this region corresponding to the maximum peak of rainfall amount on the visible image. Figure 12 shows the surface weather chart and IR satellite image of GMS at 09 JST on August 30, 1985. In this case, on the other hand, no depression existed over the Sea of Japan and the southeasterly wind on this region was caused by the outbreak from the high pressure over the Sea of Okhotsk, thus, the occurrence of such a heavy rainfall had been unexpected by many workers. A cloud band which seems to correspond to the radar echo was found over the observation area on the IR image as indicated by a white arrow, likewise.

4. Conclusions

Rainfall observations were carried out using a mobile weather radar, raingauges and wind vanes and anemometers on the southeastern slope of the Orofure mountain range from late August to early September in 1985 and 1986. In the case of rainfall from 29 to 30 August in 1985, the horizontal distribution of total rainfall amount showed two maximum peaks located in the mountainous region and near the coastline around Noboribetsu City. It was considered that they were caused by the continuous rainfall from very shallow and weak precipitating clouds maintained by the horizontal convergence of the wet air flow near the ground, and by the showery rainfall from shallow convective precipitating clouds whose echo top was lower than 3 km above sea level, respectively. And it was considered that the latter shallow convective precipitating clouds were produced by the uplifting of the wet southeasterly wind in the lower layer from the Pacific Ocean on the southeastern slope of the mountain range near the coastline, and that the cause of the shallowness of this precipitating clouds was the existence of the dry air whose relative humidity was lower than 20% upper than 700 mb level.

Up to the present, Kikuchi and his group mainly have paid their attention to the existence of a depression located to the west offshore of Akita Prefecture,

to the southeasterly wind blowing into the depression, and to the interaction between the orographic clouds in the lower layer and the upper level cloud associated with the synoptic scale disturbance as the important factors of the heavy rainfalls on this region. In this case, however, no depression existed over the Sea of Japan to the west offshore of Akita Prefecture and the southeasterly wind was caused by the outbreak from the high pressure over the Sea of Okhotsk, so it was difficult to expect the occurrence of such a heavy rainfall. Further, although the precipitating clouds near the coastline recorded 97 mm in rainfall amount for 12 hrs, the height of this echo top was lower than 3 km. Therefore, the routine radar observations by JMA at Sapporo and Hakodate could not find them. It must be recognized therefore that a heavy rainfall can occur on this region without synoptic scale disturbances, for instance, depression, front and so on.

Acknowledgments

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