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Airflow Circulations in the Precipitation Clouds over the Southeastern Slope of the Orofure Mountain Range, Hokkaido, Japan

Koyuru Iwanami*, Katsuhiro Kikuchi, Hiroshi Uyeda and Takashi Taniguchi**

Department of Geophysics, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan

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Abstract

Doppler radar observations were carried out from late August to early September in 1989 for the main purpose of investigating rainfall systems around the isolated mountain, Mt. Yotei. The southeastern slope of Orofure mountain range was located within the radar coverage and Doppler velocity data which gave information concerning the airflow in the precipitating clouds over this area were obtained for the first time.

The VVP method is considered to be effective in order to retrieve horizontal wind fields from single Doppler radar analysis, although some problems exist in regard to the observed data quality, data recording mode, etc. It was demonstrated that effects of the topography were produced on the horizontal winds in the lower layer when the wind direction was east-southeast to south. Namely, the horizontal winds were divided by the ridges stretching southeastward and came together between the ridges, and the resulting convergence enhanced precipitation clouds. This influence of the topography was not apparent when winds were weak and their westerly components were large. Additionally, the airflow circulation in the band-shaped precipitation echoes on the RHI cross section determined from the assumption of two-dimensional flow and vertical integration of calculated divergence accounted well for the reflectivity distribution.

1. Introduction

Orographic rainfall has been actively studied to date, particularly in the South Wales hills in the British Isles (Browning et al., 1975 ; Hill et al., 1981), in

* Present affiliation : Nagaoka Institute of Snow and Ice Studies, National Research Institute for Earth Science and Disaster Prevention, Nagaoka 940-0821, Japan

** Present affiliation : Hokkaido Head Office, Japan Weather Association, Sapporo 064-8555, Japan

the Owase area in the Kii Peninsula (Takeda et al., 1976 ; Takeda and Takase, 1980), and in the Orofure mountain range in Hokkaido, Japan. It is generally accepted that the annual mean rainfall amount and the times of heavy rainfalls on Hokkaido Island are smaller than those in other districts in Japan. However, on the southeastern slope of the Orofure mountain range facing the Pacific Ocean in the southwestern part of Hokkaido, there is a relatively large annual mean rainfall, and heavy rainfalls amount to more than 90 $mmday^{-1}$ three or four times per year (Takeda and Kikuchi, 1978). This area has been frequently subjected to floods and landslides arising from heavy rainfalls (Harimaya et al., 1981). If the mechanisms of heavy rainfalls are clarified, the flood and damage they result in could be reduced through adequate rainfall forecasts.

Kikuchi and his group have studied the heavy rainfalls in this region since 1978. Konno and Kikuchi (1981) classified the horizontal distribution of rainfall amount into five types according to the locations where the maximum peak of rainfall amount was located based on the results of observations using their special mesoscale raingauge network. They clarified that the distribution patterns were mainly influenced by the wind direction in the lower layer. Konno et al. (1981) made the observations on the size distribution of raindrops at two observation sites simultaneously in the mountain range and at the seaside of the same area. The results of their observations suggested that the heavy orographic rainfalls in this range arose from a combination of lower layer clouds caused by an uplifting of the warm and wet air from the Pacific Ocean on the southeastern slope of the range and the precipitation from the upper layer 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 Iwanami et al. (1988) clarified the enhancement of the rainfall amount by the two-layer cloud structure model (Bergeron, 1965) through their radar observation.

Kikuchi et al. (1988) further pointed out the importance of the role of the horizontal convergence in the increase of rainfall amounts on the mountainous regions because the valley became narrower from the seaside to the mountain side. This was noted in the results of their observations and numerical experiments. Tobizuka and Harimaya (1989) made a case study of seaside rainfalls in which the maximum peak of rainfall amount was located in the seaside region. It was shown that seaside rainfall was formed through a process in which echo cells, because of the discontinuity in the surface roughness, developed rapidly on the southeastern slope after crossing over the ridge of the range by frictional convergence. Iwanami et al. (1989) also reported seaside rainfall from the shallow convective precipitating clouds with echo tops lower than 3 km formed by a southeasterly flow of outbreak from the high pressure over the Okhotsk Sea. Iwanami et al. (1997) further described the results of case studies of two heavy rainfall cases caused by the stratiform and convective precipitation clouds. Iwanami et al. (1998) reported the heavy rainfall case where the passing of an internal gravity wave was one of the mechanisms which enhanced rainfall amount.

It seems that two subjects, that is, three-dimensional airflows and microphysical processes in the precipitation clouds, remain to be solved in order to further understand the heavy rainfall mechanisms in this area. In this paper, we describe the results of Doppler radar observation carried out in this area for the first time in 1989. Airflows in the precipitation clouds over the southeastern slope of the Orofure mountain range are estimated mainly by the VVP method.

2. Observations

Doppler radar observations were carried out at Naruka, Toya Village from late August to early September in 1989 for the main purpose of investigating rainfall systems around the isolated mountain, Mt. Yotei. The southeastern slope of Orofure mountain range was located within the radar coverage and the Doppler velocity data which gave information concerning of the airflow in the precipitating clouds over this area were obtained.

The southeastern slope of the Orofure mountain range running nearly parallel to the coastline faces the Pacific Ocean from Tomakomai (tentative site name: TOM) through Shiraoi (SHR), Noboribetsu (NOB) to Muroran (MUR), thus the orographic rainfalls caused by the orographic uplifting of the warm and wet southeasterly airflow from the Pacific Ocean occur frequently in this area. The special raingauge network as in 1985 and 1986 observation periods (Iwanami et al., 1997) was not set up in the area, so surface rainfall amounts at the meteorological observatories, AMeDAS and the rainfall amount measuring robots provided by the Japan Meteorological Agency (JMA) were used alone for the analysis. In Fig. 3, the locations of our Doppler radar site and surface observation sites by JMA are represented by their respective symbols. The Ohtaki-AMeDAS by JMA (OTK) is located on the northwestern slope of the Orofure mountain range.

The mobile weather radar of the Faculty of Science, Hokkaido University with a 9,410 MHz frequency, 40 kW peak transmitting power and resolution of 250 m in radial and 1.0 degree in azimuthal direction was supplemented with the

Doppler function in 1988. The Doppler radar had ±12.0 m/s Nyquist velocity, 0.4 μs pulse duration, 1500 Hz pulse repetition frequency.

3. Results

Three cases of rainfalls when precipitation clouds widely covered the southeastern slope were analyzed, and their surface weather charts and typical PPI radar echoes are shown in Figs. 1 and 2, respectively. The single Doppler radar analyses were carried out by means of the VAD method (Lhermitte and Atlas, 1961 ; Browning and Wexler, 1968) and VVP method (Waldteufel and Corbin, 1979 ; Koscielny et al., 1982), and a two-dimensional airflow calculation was conducted on the RHI cross section (cf. Wang and Hobbs, 1983).

3.1 Case 1 (27-28 August 1989)

The rainfalls on August 27 to 28 in 1989 were associated with the Typhoon 8917. The typhoon, that existed over Hokuriku District at 21 JST on August 27 as shown in Fig. 1(a), moved northeastward and passed over the east side of the radar site. The southeasterly winds blew over the observation area in front of this typhoon. According to the aerological data of Sapporo at the same time, a moist and convective neutral layer extended to over 4.0 km a.s.l.

Figure 2(a) shows 4.0° PPI images of reflectivity (left) and Doppler velocity (right) at 02 : 46 JST on August 28. Judging from the reflectivity picture and with reference to the crestline, a wide echo area weaker than almost 27 dBZ spread over the southeastern slope of the mountain range, although an echo free area south-southeast of the radar site is a shadow zone. The plus and minus values of Doppler velocity as shown in the right picture demonstrate the radial velocity toward and away from the radar site, respectively. The echoes of Doppler velocity have a little wider area than those of reflectivity because of higher sensitivity. Since our Doppler radar has the Nyquist velocity of ±12.0 m/s, the velocity unfolding must be carried out for the radial velocity values larger than 12.0 m/s or smaller than −12.0 m/s. The velocity maxima exceeded 24.0 m/s in this PPI image and the velocity unfolding was carried out two times. The wind direction in the lower layer was assumed to be east-southeast judging from the 0 m/s line, however, a vertical profile of the wind is shown later in detail

The horizontal distribution of the total rainfall amount for this case is shown in Fig. 3. The rainfall amount was distributed over a wide area, however the maximum peak was located in the mountainous region on the southeast-

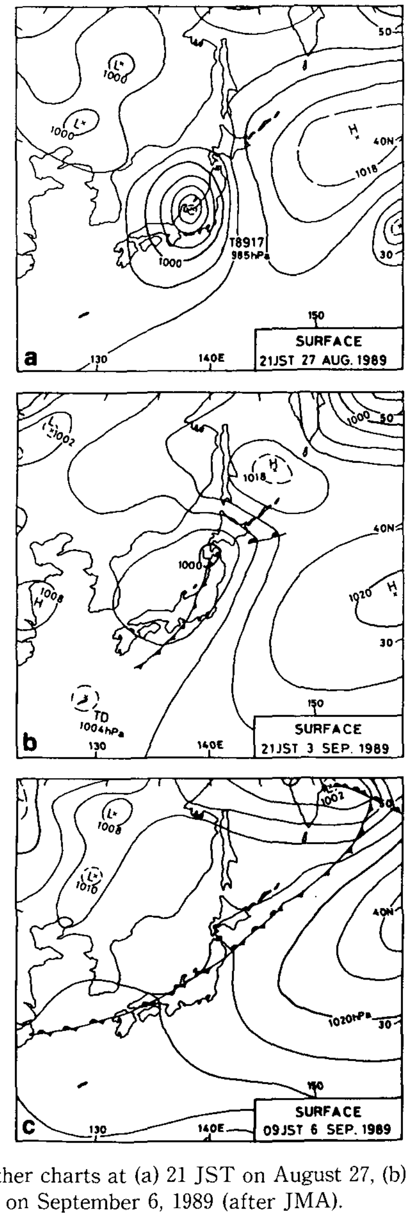
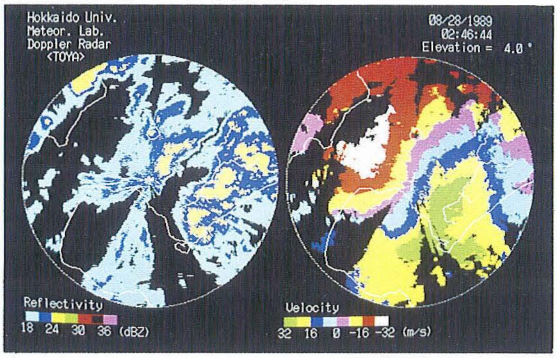
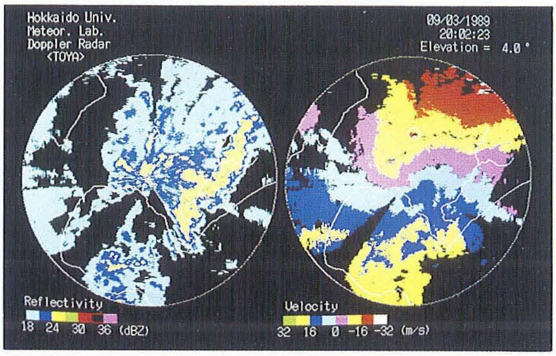


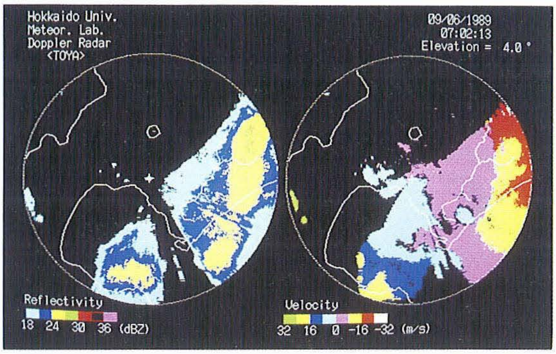
Fig. 1. Surface weather charts at (a) 21 JST on August 27, (b) 21 JST on September 3 and (c) 09 JST on September 6, 1989 (after JMA).



(a)



(b)



(c)

Fig. 2. PPI pictures of elevation angle of 4.0° at (a) 02 : 46 JST on August 28, (b) 20 : 02 JST on September 3 and (c) 07 : 02 JST on September 6, 1989. Left and right images represent reflectivity and Doppler velocity (+ : toward and − : away from the radar site) in each time, respectively, and their color scales are shown in lower part. The range circle of 60 km, coastline and crestline of the Orofure mountain range are drawn.

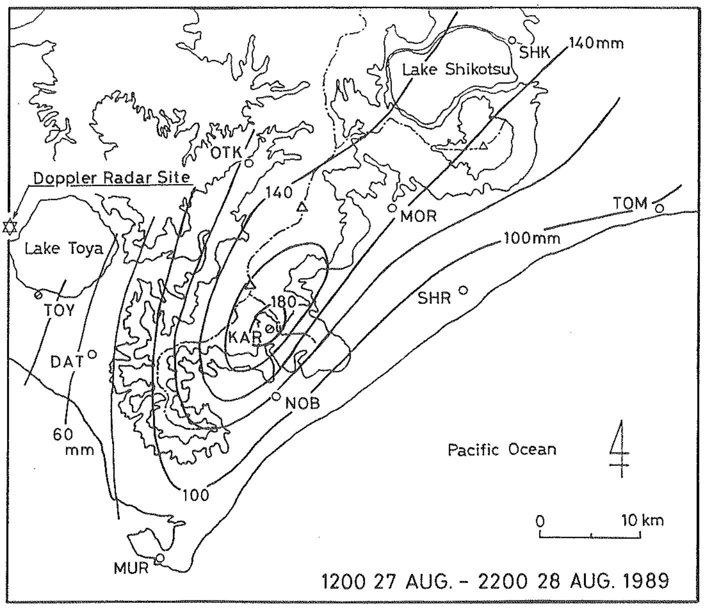


Fig. 3. Horizontal distribution of total rainfall amount from 12 JST on August 27 to 27 JST on August 28, 1989. The contours of rainfall amount are drawn at 20 mm intervals from 40 mm. The locations of meteorological observatories, AMeDAS (○) and rainfall measuring robots (⊘) provided by JMA are represented by symbols and the Doppler radar site is also shown.

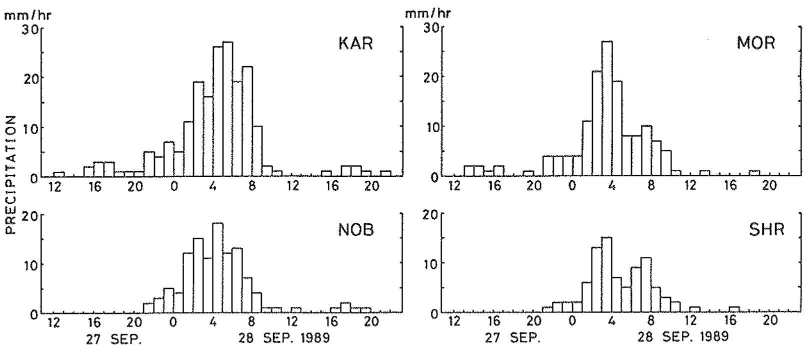


Fig. 4. Time series of 1 hr rainfall intensity at four AMeDAS stations by JMA.

ern slope parallel with the watershed centered on Karurusu (KAR) where the total rainfall amounted to 193 mm.

Figure 4 represents the time series of the rainfall intensity for 1 hour at four AMeDAS sites. The two top sites KAR and MOR are located in the mountain-

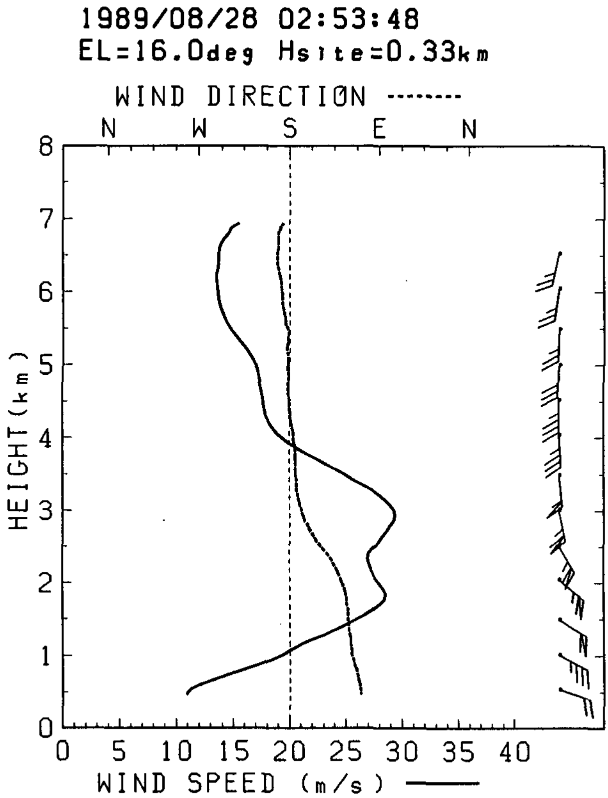


Fig. 5. Vertical profiles of with speed and direction above Doppler radar site retrieved by applying the VAD method to Doppler velocity data on 16.0° PPI image at 02 : 53 JST on August 28, 1989 drawn by thick solid (lower abscissa) and dashed line (upper abscissa), respectively. Wind profiles are also indicated by flag (20 m/s), full barb (5 m/s) and half barb (2.5 m/s) at 0.5 km intervals.

ous while the lower sites NOB and SHR are in the seaside regions, respectively. It is found that the heavier rainfalls were recorded in the mountainous region than in the seaside region, and maximum intensity of 27 mm/hr was recorded at Karurusu (KAR) for 05-06 JST and at Morino (MOR) for 03-04 JST. Our attention is paid to the precipitation clouds which widely spread over the observation area for 02-03 JST on August 28 as shown in Fig. 2(a).

Figure 5 represents the vertical profile of horizontal wind over the radar site derived from applying the VAD method to Doppler velocity data on a 16.0° PPI image at 02 : 53 JST. The Velocity Azimuth Display (VAD) method (Lhermitte and Atlas, 1961 ; Browning and Wexler, 1968) is a technique for the measurement of kinematic properties of a wind field in a situation of widespread homogeneous precipitation using a single Doppler radar. We can estimate horizontal winds therefore at a succession of altitudes by scanning the radar beam about a vertical axis at a fixed elevation angle. Although Browning and Wexler (1968) proposed a technique based on harmonic analysis, the numerical procedure used here followed Tsuboki and Wakahama (1988) which was based on a least-square-fitting method, that is, fitting radial velocities observed on a scanning circle to a sine curve. According to Fig. 5, the wind direction was east-southeast to south-southeast below 3.0 km a.s.l. and south over the same level. The wind speed was very strong over a wide range associated with the typhoon and the maxima were found at 1.8 and 3.0 km a.s.l.

The Velocity Volume Processing (VVP) method (Waldteufel and Corbin, 1979 ; Koscielny et al., 1982) was also developed for the retrieval of kinematic variables from single Doppler radar observations assuming that the wind field is spatially linear and time invariant over the scan period. Although the VAD method uses only radial velocity data on a scanning circle, the VVP method makes full use of them filling a volume, termed analysis volume, by volume scanning. The analysis method proposed by Koscielny et al. (1982), based on statistical multivariate regression, was applied to our single Doppler radar data. Long et al. (1990) and Sassen et al. (1990) investigated a winter mountain storm in Utah, U.S.A. with an application of the VVP analysis to their single C-band Doppler radar data.

A sector whose spacings of elevation angle, azimuth angle and range were 1.0° or 2.0°, 30° and 15 km, respectively, was selected as the analysis volume here. The sector contained about 4000 radial velocity data. Horizontal wind distributions were derived by shifting the analysis volume by 10° or 15° in azimuthal and 5.0 km in radial directions. The errors in estimations of wind direction and speed were several degrees and about 1.0 m/s, though this does not contain the errors for observed Doppler velocity.

The left panel of Fig. 6 shows the horizontal wind field in the precipitation clouds shown in Fig. 2(a) retrieved by applying the VVP method to 3.0° and 4.0° PPI data. Since Doppler velocity data on two PPI images which had been recorded at different elevation angles were used for calculation, the estimated points (centers of analysis volumes) had higher altitudes at longer ranges from the radar site. For example, the altitudes of estimated points were about 2.0 km a.s.l. over the crestline and about 3.0 km over the coastline. Namely this wind field includes the effects of the vertical wind shear, and the vertical profile of mean horizontal wind derived from the VAD method as shown in Fig. 5 is also

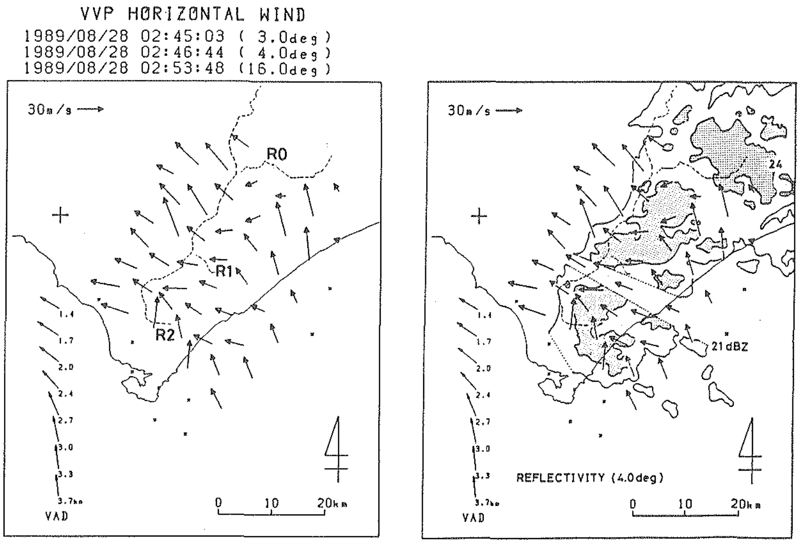


Fig. 6. Left panel: Distribution of horizontal winds retrieved by applying the VVP method to Doppler velocity data on two PPI images at 3.0° and 4.0° at 02:45 and 02:46 JST on August 28, 1989. Vertical profile of the horizontal wind by the VAD method is also shown in lower left with numerals indicating altitudes (km a.s.l.). Winds are represented by arrows whose scale is shown in upper left. A large plus and small cross, solid and dashed lines indicate Doppler radar site and resultless point, coastline and crestline, respectively. Right panel: As in the left panel, but superimposed by 4.0° PPI reflectivity. The echo intensities are indicated by contours for 21 and 24 dBZ and echo areas stronger than 24 dBZ are stippled.

represented in the lower left as a reference. Unfortunately, horizontal winds over the southeastern slope below 2.0 km a.s.l. could not be estimated since the Doppler radar site was set up on the northwestern side of the mountain range. According to this wind field, it was found that the horizontal winds came together among the ridges (R0, R1 and R2) stretching southeastward. The echo intensity shown in the right panel of Fig. 6 was strengthened between the two ridges, R1 and R2. It is therefore considered that the horizontal airflow in the precipitation clouds over this area was influenced by the topography and the echo intensity was enhanced by this airflow convergence.

Further, the horizontal wind fields on higher levels were calculated from application of this method to the Doppler velocity data on 6.0°, 8.0° and 9.9° PPI images and they are shown in Fig. 7. The wind shift affected by the topography as shown in Fig. 6 did not appear at higher levels and it was found that the wind fields were comparatively uniform and nearly the same as the winds retrieved by

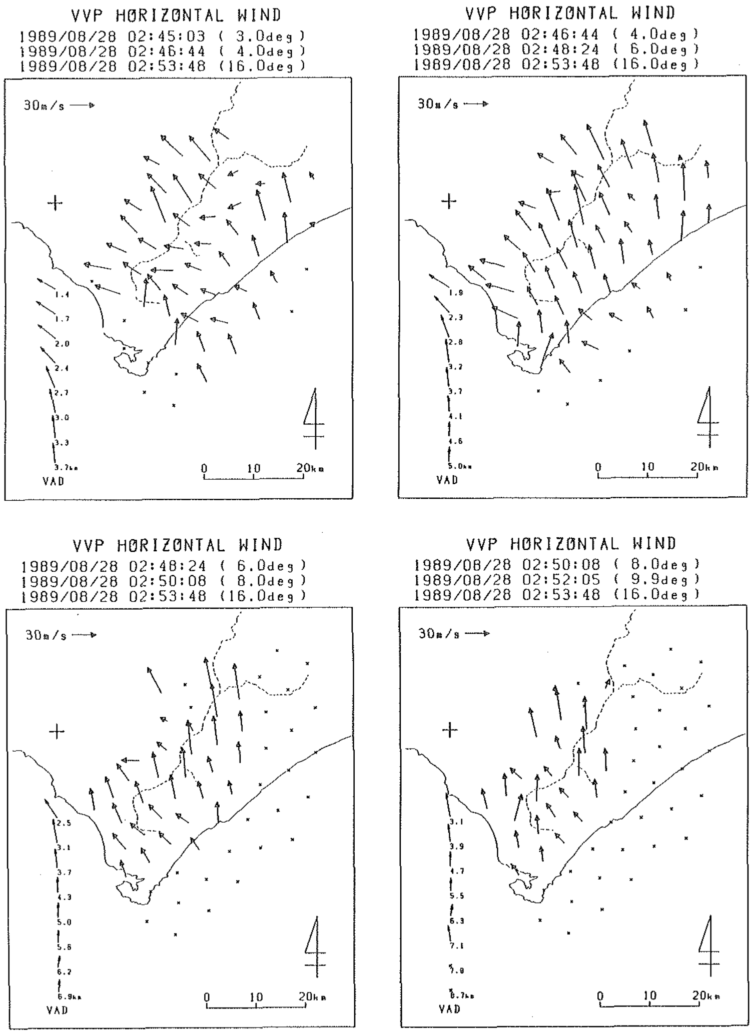


Fig. 7. Horizontal wind fields retrieved by applying the VVP method to Doppler velocity data on 3.0° and 4.0°, 4.0° and 6.0°, 6.0° and 8.0°, and 8.0° and 9.9° PPI images. The recorded time of each PPI images is shown at the top of each panel. Other representations are the same with the left panel in Fig. 6.

applying the VAD method at higher levels. It is considered that the altitude range where winds were influenced by the topography was limited to below about 3.0 km a.s.l. in this case, when the wind direction in the lower was east-southeast to south-southeast.

3.2 Case 2 (3-4 September 1989)

The rainfalls on September 3 in 1989 were associated with the low pressure shown in Fig. 1(b). This depression traveled north-northeastward over the Japan Sea along the west coast of the Japan Islands and approached together with a warm front near the observation area at 21 JST on September 3. The surface wind direction over the observation area was southeasterly, considered a suitable situation for the heavy rainfalls.

Figure 8 shows the time series of rainfall intensity for 1 hour at four AMeDAS sites. The horizontal distribution of the rainfall amount could not be drawn because of the trouble of the Ohtaki AMeDAS (OTK in Fig. 3). The sites of KAR and MOR in the mountainous region recorded 114 and 140 mm, respectively, which were more than the rainfall recorded in the seaside region (NOB ; Noboribetsu and RHR ; Shiraoi). The rainfall intensity in the mountainous region was especially strong around 20 JST on September 3 when the band-shaped precipitation echoes associated with the warm front passed over the southeastern slope of the mountain range. The band-shaped echo is demonstrated in Fig. 2(b) and it approached this area from the south and developed to be stronger than 30 dBZ over the southeastern slope of the range.

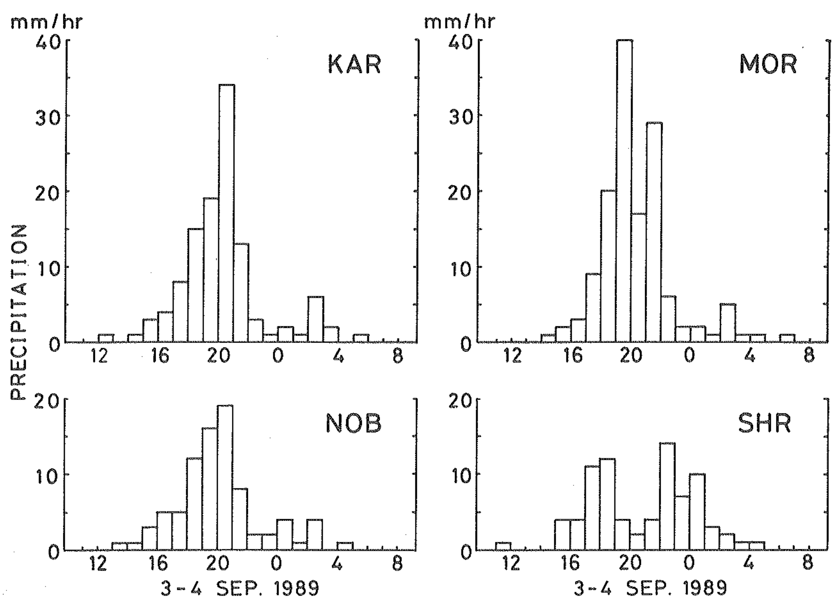


Fig. 8. As in Fig. 4, but for September 3 to 4, 1989.

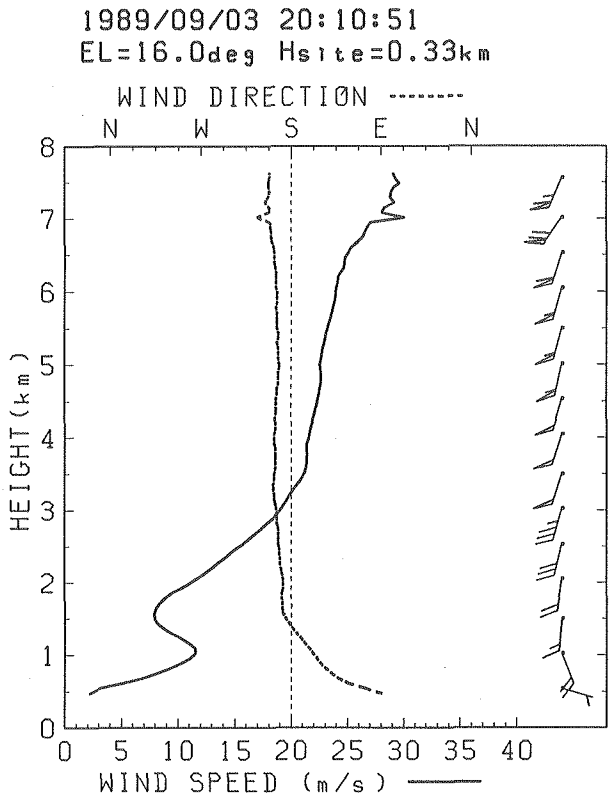


Fig. 9. As in Fig. 5, but for 20 : 10 JST on September 3, 1989.

The vertical profile of horizontal wind above the radar site was derived from the VAD method as shown in Fig. 9. The wind direction was east-south-east to south below 1.5 km a.s.l. and south-southwest over the level. Although the maximum speed was found at 1.0 km a.s.l., the wind speed closely increased with height. The horizontal wind field retrieved by applying the VVP method in Fig. 10 demonstrated nearly the same features as in Fig. 6. Namely it was found that the airflow from the Pacific Ocean was modified by the topography and converged between two ridges stretching southeastward in the lower layer.

Figure 11 shows RHI pictures of reflectivity (top) and Doppler velocity (bottom) in the perpendicular direction to the band-shaped echo at 20 : 14 JST on September 3. This direction was also approximately parallel with the wind direction in the lower layer as indicated in Fig. 9. The crest of the mountain range in this direction was located at 25 km from the radar site (open triangle ;

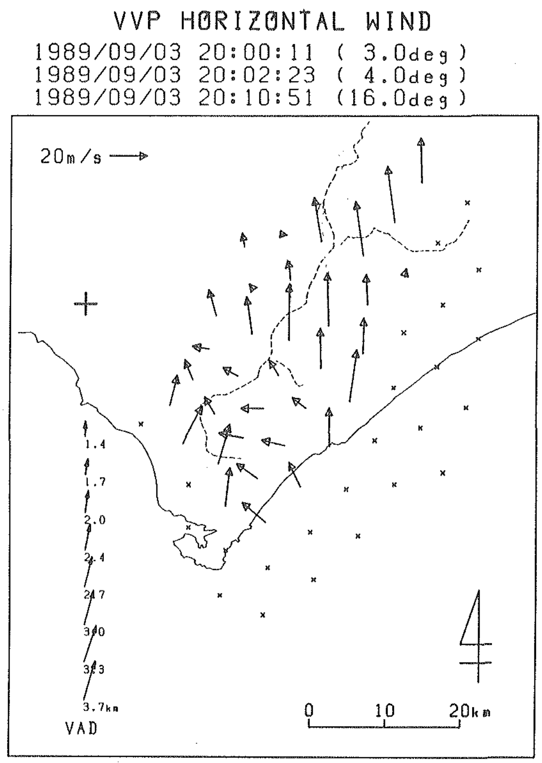


Fig. 10 As in left panel of Fig. 6, but for 20 : 00 and 20 : 02 JST on September 3, 1989.

R). The figure shows that the precipitation cloud developed over the ridge into 27 to 30 dBZ in reflectivity and the echo top height reached 6.5 km (reflectivity) or 7.8 km a.s.l. (velocity).

By using the Doppler velocity data on the RHI image (bottom panel in Fig. 11), airflow on the vertical cross section was estimated (cf. Wang and Hobbs, 1983). It was assumed in this calculation that the winds in the perpendicular direction to this RHI cross section scarcely changed on both sides, that is to say, the airflow was two-dimensional. This assumption was adequate as least in the lower layer since the RHI image was recorded in the direction parallel with the horizontal wind. Firstly, the horizontal winds along the cross section were calculated at the grid points with horizontal and vertical intervals at 1.0 and 0.5 km, respectively, by assuming the constant terminal velocity of precipitation particles. Then mean horizontal winds at 0.5 km intervals identified by the VAD method were subtracted from these winds and the horizontal divergence

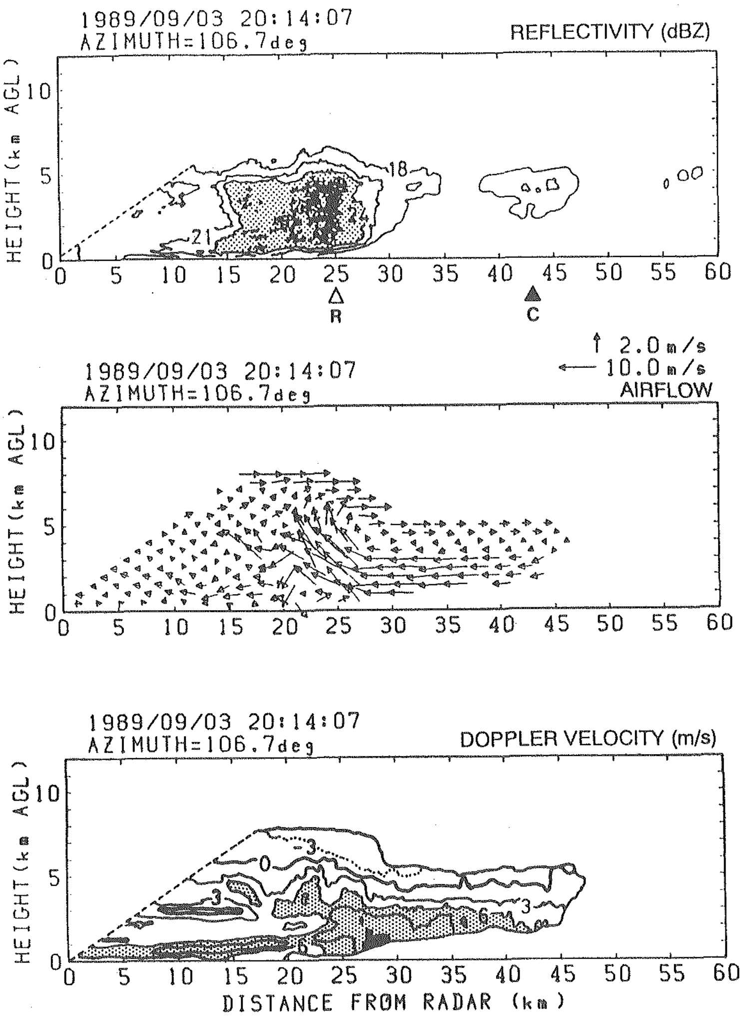


Fig. 11. Distribution of reflectivity (top), Doppler velocity (bottom) and calculated airflow (middle) on the RHI cross section of azimuth of 106.7° at 20 : 14 JST on September 3, 1989. The reflectivity is indicated by contours at 3 dBZ intervals from 18 dBZ and echo areas stronger than 24 and 27 dBZ are stippled and blacked out respectively. Doppler velocity (+ : toward and − : away from radar site) is indicated by contours at 3 m/s intervals and echo areas with velocity faster than 6 and 12 m/s stippled and blacked out, respectively. The airflow is represented by arrows whose scales are indicated in upper right of the middle panel. Small open (R) and solid triangles (C) indicate the locations of ridge and coast on the cross section, respectively.

values were calculated from these velocity perturbations. Further, the divergence values were integrated downward from the echo top and vertical winds were determined. The vertical components of Doppler velocity recorded at high elevation angles of the RHI scan were used as the upper boundary condition at the echo top. Since the bottom boundary condition where vertical winds at the ground surface were zero was prescribed, the residuals at the ground surface, if they existed, were distributed above according to the divergence values. The residuals at the ground surface were very small for this RHI data.

Thus the derived airflow on the RHI cross section is represented in the middle panel in Fig. 11. Note that the vertical wind scale is 2.5 times larger than the horizontal scale as indicated in the upper right of the panel. The strong horizontal winds flowed in over the southeastern slope of the mountain range from the seaside in the lower layer below 3.0 km a.g.l. (height of the Doppler radar site was 0.33 km a.s.l.) and it is considered that they supplied the precipitation clouds with abundant water vapor and liquid water from over the ocean (solid triangle : C indicates the location of the coast). They became the updrafts which reached about 4.0 m/s over the ridge (open triangle ; R) and the location of strong updrafts corresponded to the developed echo areas stronger than 27 dBZ shown in top panel. The backward flow was found in the weak echo region close to the echo top and upper part of the strong inflow. It is therefore recognized that a reasonable airflow in the band-shaped precipitation clouds was estimated on the RHI cross section.

3.3 Case 3 (6 September 1989)

The third rainfall case occurred on September 6, 1989. The surface weather chart in Fig. 1(c) demonstrated that a widespread trough covered all of the Japan Islands, and the convective unstable layer extended to 3.0 km a.s.l. judging from the aerological data at Sapporo. Rainfall amounts of only 3 to 6 mm were observed around the Orofure mountain range and those on the seaside region were relatively larger than in the mountainous region. This rainfall was caused by weak stratiform precipitation clouds shown in the PPI pictures at 07 : 02 JST in Fig. 2(c) and wide echo areas stronger than 24 dBZ corresponded to the bright band.

The vertical profile of the mean horizontal wind at 07 : 08 JST by VAD method is shown in Fig. 12. It was found that weak southerly or southwesterly winds blew below 2.0 km a.s.l., however a wind shear appeared at 2.0 km and the wind direction changed into west-northwest to southwest over that level. Wind speed was less than 10.0 m/s below 3.0 km a.s.l. and the feature of the profile was

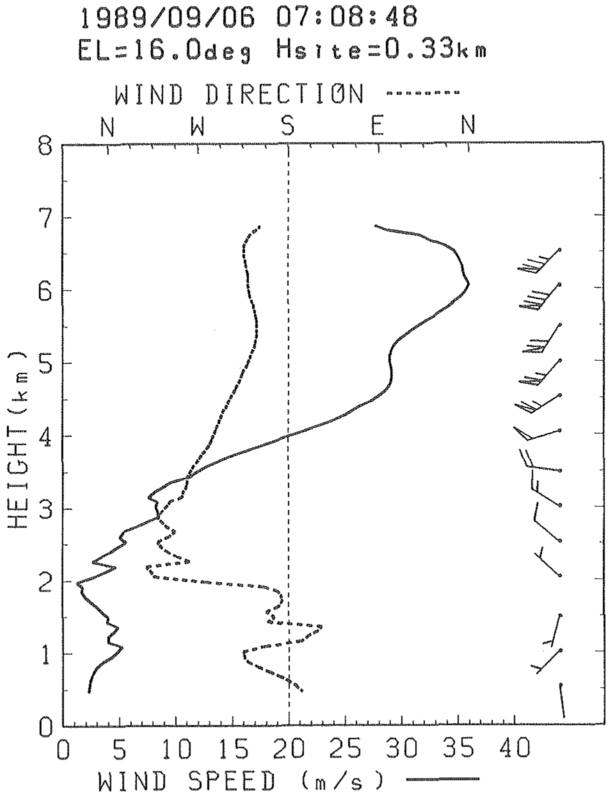


Fig. 12. As in Fig. 5, but for 07 : 08 JST on September 6, 1989.

considerably different from the previous two cases.

Figure 13 indicates horizontal wind fields retrieved by applying the VVP method for this case. The winds were weak in the lower layer and approximately similar to the mean horizontal winds identified by the VAD method over the entire layer. These winds were also different from the two cases discussed above. It is therefore concluded that the effects of topography on the airflow in the precipitation clouds were not produced when winds were weak and the westerly component was remarkable, but when east-southeasterly to southerly winds were predominant in the lower layers the effects of topography on the airflow were pronounced.

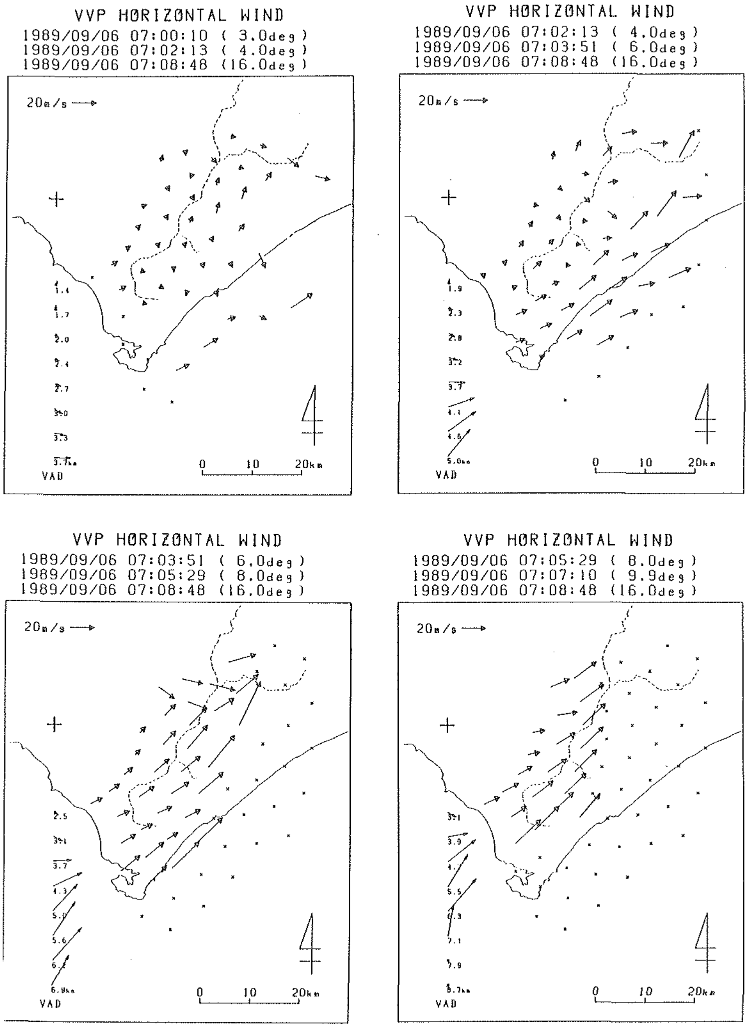


Fig. 13. As in Fig. 7, but for 07 : 00 to 07 : 08 JST on September 6, 1989.

4. Conclusions

The airflows in the precipitation clouds over the southeastern slope of the Orofure mountain range were estimated for the first time by Doppler velocity data gathered in the summer season in 1989. The VVP method is considered to be effective in order to retrieve horizontal wind fields from single Doppler radar analysis, although some problems exist in regard to the observed data quality, data recording mode, etc. It was demonstrated that effects of the topography were produced on the horizontal winds in the lower layer when the wind direction was east-southeast to south. Namely, the horizontal winds were divided by the ridges stretching southeastward and came together between the ridges and the resulting convergence enhanced precipitation clounds. This influence of the topography was not apparent when winds were weak and their westerly components were large. Additionally, the airflow circulation in the band-shaped precipitation echoes on the RHI cross section determined by the assumption of two-dimensional flow and vertical integration of calculated divergence accounted well for the reflectivity distribution.

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