A Study of the Heavy Rainfall over the Ohsumi Peninsula (Japan) Caused by Typhoon 9307

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Abstract

On the night of 9 August 1993, Typhoon 9307 passed near the southern part of Japan and caused heavy rainfall and many land-slide disasters across the Ohsumi Peninsula. A notable feature of this event is that the rainfall amount was very large on the lee side of the mountains. The 9-hour rainfall exceeded 150 mm at the greater part of the stations on the lee side, while it was only 80 mm at the station on the windward side. All the land-slide disasters occurred on the lee side. The heavy rainfall was mainly produced between the eyewall and the rainband of the typhoon. Radar echoes showed strong reflectivity over the mountains during the rainfall event.

The rainfall increasing process was studied by using a two-dimensional numerical model. The results suggested that the seeder-feeder mechanism contributed to the rainfall enhancement on the lee side. Namely, the precipitating particles from the upper cloud grew over the mountains by accreting cloud water produced by the orographic lifting, and the grown particles were carried to the lee side by the strong wind of the typhoon. In addition, it was also suggested that the downdraft of the mountain wave made an additional contribution to the rainfall enhancement by transporting many ice particles to the lower layer.

1. Introduction

On the night of 9 August 1993, Typhoon 9307 passed near the southern part of Japan. Due to the passage of the typhoon, the local daily amount of rainfall exceeded 250 mm and many land-slide disasters occurred across the Ohsumi Peninsula located at the southernmost part of Kyushu. A notable feature of this event is that the rainfall amount was very large on the lee side of the mountains. The 9-hour rainfall exceeded 150 mm at the greater part of the stations on the lee side, while it was only 80 mm at the station on the windward side. All of the land-slide disasters occurred on the lee side of the mountains.

It is well known that the rainfall from a tropical cyclone is enhanced around mountains (Staff Members of Tokyo University, 1969, 1970; Sakakibara and Takeda, 1973; Sinclair, 1993). In many cases, however, the rainfall increases on the windward side rather than on the lee side. For example, the rainfall of Typhoon 7002 was very large on the windward side of the Kii peninsula, while it was very small on the lee side (Sakakibara and Takeda, 1973). The rainfall over New Zealand caused by Cyclone Bola showed extremely large amounts on the windward

side of the mountains (Sinclair, 1993).

Generally the enhancement of rainfall around mountains is explained by the “seeder-feeder mechanism” proposed by Bergeron (1965). He proposed that the precipitating particles from the upper cloud (seeder cloud) wash out the orographically produced cloud in the lower layer (feeder cloud). Bergeron’s idea was supported by many observations carried out later. For example, Browning *et al.* (1974) found a close spatial agreement between the rainfall pattern and the topography around the south Wales hills. Hill *et al.* (1981) showed the radar echoes were actually enhanced in the lower layer above the mountains. In Japan, Harimaya *et al.* (1988), Harimaya and Tobizuka (1988) and Iwanami *et al.* (1988) observed precipitating systems passing over the Orofure mountain range. They showed the heavy rainfall was produced by the interaction between the clouds of mesoscale disturbances and those produced by the orographic uplift. Theoretical studies and numerical simulations also supported the importance of the seeder-feeder mechanism (Bader and Roach, 1977; Gocho, 1978; Carruthers and Choularton, 1983; Richard *et al.*, 1987; Kikuchi *et al.* 1988). It is considered that the mechanism strongly acts when a typhoon passes near a mountain, since the strong low-level wind of

the typhoon produces dense orographic clouds.

The seeder-feeder mechanism is affected by the horizontal wind and the shape of mountains. Carruthers and Choularton (1983) studied these effects with the use of a numerical model. They showed that the position of the largest increment rate shifted to the lee side when the wind was strong and the mountain width was small. Gocho (1978) simulated the heavy rainfall which occurred over a narrow mountain range. He showed that the heaviest rainfall was on the lee side of the mountain crest. However, the heavy rainfall was produced only near the peak of the mountain in these studies. In our case the strong-rainfall region extended even over the plain to the lee side.

In this paper we describe the characteristics of the heavy rainfall over the Ohsumi Peninsula caused by Typhoon 9307 by using the rain-gauge data and the radar-echo patterns. Then we perform two-dimensional numerical simulations and discuss the rainfall-increasing process in this case.

2. Characteristics of the rainfall event

a. Precipitation systems

Figure 1 shows the distribution of the sea-level pressure at 21 JST (Japan Standard Time, UTC+

Fig. 1. Horizontal distribution of the sea-level pressure at 21 JST on 9 August, 1993. The contours are drawn every 4 hPa. The frame in the figure corresponds to the region shown in Fig. 2.

Fig. 2. Distributions of hourly amounts of the rainfall in 17–18 JST on 9 August and 01–02 JST on 10 August, 1993. The amounts are estimated by the rain-gauge data and the radar-echo intensity derived from the PPI radar at Tanegashima. The radar site is denoted by $\circ$ in the left figure. The frames indicate the Ohsumi Peninsula.

9h) on 9 August 1993. The low pressure region to the southwest of the Japan Islands is Typhoon 9307. This typhoon formed on 1 August at 7°N and 154°E. It developed with movement towards the northwest and reached its maximum strength at 09 JST on 9 August. At that time the surface pressure near the center was 940 hPa, and the maximum wind velocity at the surface was 45 m/s. The typhoon approached the southern part of Kyushu 12 hours after attaining its maximum strength. At this time the surface pressure near the center was still 940 hPa.

Figure 2 shows the horizontal distributions of the hourly amounts of rainfall in 17–18 JST on 9 August and 01–02 JST on 10 August. The rainfall amounts were evaluated by the radar-echo reflectivity derived from the PPI radar at Tanegashima, whose location is denoted by $\circ$ in the figure. The estimated amounts were corrected by the data measured by rain gauges. These data (Radar-AMeDAS Composite Data) are routinely created by the Japan Meteorological Agency (JMA). The details of the estimation method are reported by Takemura (1983). The estimated amounts are not always quantitatively accurate, but they are convenient for the elucidation of the qualitative features of the precipitation systems. In 17–18 JST the eye of the typhoon was located around 29.5°N and 129°E. The circular rainfall region surrounding the eye is the eyewall of the typhoon. The rainfall amount in the eyewall locally exceeds 20 mm, which suggests the existence of deep convective clouds. A band-shaped rainfall region, which extends from the northwest to the southeast in the left figure, is one of the rainbands of the typhoon. It also includes a strong rainfall region.

The frames in the figure denote the location of the Ohsumi Peninsula. It is covered with a weak and broad rainfall region between the eyewall and

the rainband in 17–18 JST. The strong rainfall region over the radar site is considered to be an error in the radar-echo reflectivity, because the corresponding strong rainfall was not recorded by the rain-gauge data. In 01–02 JST the typhoon has moved to the north. The averaged movement speed is 27 km/h, which is relatively slow for a typhoon around Japan. In 01–02 JST the Ohsumi Peninsula is still between the eyewall and the rainband. According to the radar-echo patterns derived from the PPI radar (not shown), the Ohsumi Peninsula had been between the eyewall and the rainband during the period from 17 JST to 02 JST.

Figure 3 shows the variation of 10-minute rainfall at Kagoshima City, which is located just northwest of the Ohsumi Peninsula (Fig. 2). Because the data of 10-minute rainfall were not available at the stations on the Ohsumi Peninsula, we used the data at Kagoshima City instead. It shows a very large value around 15 JST. The rainfall intensity at 14.50 JST reaches 13 mm/(10 min), namely, 78 mm/h. This heavy rainfall corresponds to the passage of the rainband shown in Fig. 2. After the passage of the rainband, weak and continuous rainfall was recorded until 2.20 JST on 10 August.

Here we define two rainfall periods (Fig. 3). The first period, called Period 1, is from 14.00 to 17.00 JST. In Period 1 the rainband of the typhoon passed over the Ohsumi Peninsula. The second period, called Period 2, is from 17.00 to 2.00 JST. The Ohsumi Peninsula had been between the eyewall and the rainband during this period (Fig. 2). The total rainfall amount averaged over the Ohsumi Peninsula was 41.7 mm in Period 1, while it was 141.0 mm in Period 2. This suggests the heavy rainfall was mainly produced by the clouds between the eyewall and the rainband. In this study we will pay our

Fig. 3. Time variation of the 10-minute rainfall at Kagoshima City.

Fig. 4. Vertical profiles of potential temperature (θ), equivalent potential temperature (θ_e), saturated equivalent potential temperature (θ_e^*) and wind velocity above Kagoshima City at 21 JST on 9 August, 1993. Flag, long and short barbs denote 50 knots, 10 knots and 5 knots, respectively.

attention to the rainfall in Period 2.

Figure 4 shows the vertical profiles of potential temperature (θ), equivalent potential temperature (θ_e) and saturated equivalent potential temperature (θ_e^*) above Kagoshima City at 21 JST on 9 August. The profile of θ_e indicates that the convectively unstable layer is restricted to below the 850 hPa level. This condition is unfavorable for the formation of a deep convective cloud. The curves of θ_e and θ_e^* are close to each other above the 850 hPa level. This indicates the air was very moist above that level. The wind was blowing from the southeast or south-southeast in the upper layer, and the wind speed exceeded 25 m/s at all the levels.

b. The rainfall pattern over the Ohsumi Peninsula

Figure 5 shows the topography on the Ohsumi Peninsula and the rainfall amount accumulated in Period 2. The symbols $\times$ indicate the locations where land-slide disasters occurred. There are two mountain ranges on the peninsula. One is the Kimotsuki Mountains, which lies along the southeast coast. The height of the peaks are in the range from 600 m to 950 m. The other is the Takekuma Mountains, which is located in the northwest of the peninsula. A small plain extends between the two mountain ranges.

We have nineteen rain-gauge stations on and around the Ohsumi Peninsula ($\bullet$). We classified these stations into four types according to their po-

Fig. 5. Topography on the Ohsumi Peninsula and the rainfall amount in Period 2 (from 17 JST on 9 August to 02 JST on 10 August). Contours of topography are drawn for 200 m, 400 m and 600 m. Contours of rainfall amount are drawn every 25 mm. Rain-gauge stations are denoted by $\bullet$. The symbol $\times$ indicates the location where land-slide disasters occurred.

sitions relative to the Kimotsuki Mountains as:

- 1) stations on the plain to the northwest of the Kimotsuki Mountains (A1–A9),
- 2) stations on the northwest slope of the Kimotsuki Mountains (B1–B4),
- 3) the station to the southeast of the Kimotsuki Mountains (C1) and
- 4) stations which are not located to the northwest nor to the southeast of the Kimotsuki Mountains (D1–D3).

The remaining two stations, denoted by E1 and E2 in Fig. 5, were not clearly classified into the above four categories.

The rainfall amount in Period 2 averaged in every type of the stations is shown in Table 1. It should be noted that the rainfall amount greatly varies according to the types of the stations. The averaged rainfall exceeds 160 mm at the first and the second type. Most of the stations in these types record more than 150 mm (Fig. 5). On the other hand, it is smaller than 100 mm in the third and the fourth type. As will be shown in Fig. 6, the southeasterly wind prevailed at the surface during Period 2. Namely, the stations in the first and the second type

Table 1. Averaged amount of rainfall in Period 2 (from 17 JST on 9 August to 02 JST on 10 August, 1993).

Stations	Rainfall amount
A1-A9	160.9 mm
B1-B4	166.0 mm
C1	80.0 mm
D1-D3	66.3 mm

were located on the lee side of the Kimotsuki Mountains, while Station C1 was located on the windward side. It is indicated that a large amount of rainfall was recorded on the lee side of the Kimotsuki Mountains in Period 2.

The three stations in the fourth type, D1, D2 and D3, were not located to the lee nor to the windward of the Kimotsuki Mountains. The rainfall amounts in these stations are very small; 67 mm, 69 mm and 63 mm, respectively. It is considered that the rainfall in these station had not been strongly enhanced by the orographic effect. The rainfall on the windward of the mountains (C1) is 80 mm, which is slightly larger than the fourth type. Figure 5 indicates all the land-slide disasters occurred on the northwestern side of the Kimotsuki Mountains. This is consistent with the fact that the heavy rainfall was observed on the lee side.

Figure 6 shows the time variations of the hourly rainfall recorded at the stations C1, A5 and A8. These stations are on the line almost parallel with the wind direction (Fig. 5). It should be noted that the hourly rainfall at A5 is always the largest of the three in Period 2, while that at C1 is always the smallest. This suggests that the rainfall had been enhanced around A5 during Period 2. On the other hand, no systematic relations are found in Period 1. The wind direction at A5 changed from the east to the south with the passage of the typhoon. This reflects the anti-clockwise circulation around the typhoon. A similar change of the wind direction was observed at the other stations on the Ohsumi Peninsula.

c. Variation of the radar-echo pattern

We analyzed the radar-echo pattern derived from the PPI radar at Tanegashima. These data were provided by the Fukuoka Meteorological Observatory of the JMA. The echo patterns were made every 7.5 minutes by compositing pictures given at three elevation angles. The intensity of radar echoes were classified into six levels and edited into the 1 km × 1 km grid boxes in the horizontal plane. The echo-top height was evaluated every hour by analyzing the pictures given at many elevation angles. The radar site is to the south of the Ohsumi Peninsula (Fig. 7a).

Figure 7b shows the time variation of the radar-echo patterns in the rectangular region denoted in Fig. 7a. We can see a strong echo moving from the south to the north from 15 JST to 17 JST. This corresponds to the passage of the rainband of the typhoon (Fig. 2). After 17 JST, another strong echo appears over the Kimotsuki Mountains. This strong echo persists during Period 2 almost at the same place. Because the typhoon system propagated toward the north in this period (Fig. 2), it is suggested that the radar echoes were successively enhanced over the mountain.

Figure 8 shows the horizontal distribution of the frequency of radar echoes stronger than Level 3. In this analysis we used 37 pictures derived at 15-minute intervals during Period 2. The strong echoes frequently appeared over the Ohsumi Peninsula. The figure shows particularly high frequency along the southeast coast, namely, over the Kimotsuki Mountains. The locations of the rain-gauge stations C1, B4, A5 and A8 are also denoted in the figure. The high frequency of the strong echoes does not always coincide with the large rainfall amount; the strong echoes more frequently appeared at Station C1 than A5, while much more rainfall was recorded at A5 (see Fig. 6). The echo-top height over the Ohsumi Peninsula were in the range from 8 km to 10 km (not shown).

3. Numerical simulation

In the previous section we showed the rainfall in Period 2 was much heavier on the lee side of the Kimotsuki Mountains than on the windward side. In this sections we will perform numerical simulations and discuss how the rainfall was enhanced on the lee side.

Fig. 6. Time variations of hourly amounts of rainfall at stations A5, A8 and C1, and the variation of the surface wind at A5. Flag and barbs denote 5 m/s and 1 m/s, respectively.

Fig. 7. (a) The Ohsumi Peninsula and the site of the Tanegashima radar. (b) Time variation of the radar echoes in the rectangular region denoted in (a). Radar echoes stronger than level 1 and level 3 are represented by light and dark shaded areas, respectively. Black areas represent the radar echoes stronger than level 4. Broken lines indicates the location of the Kimotsuki Mountains.

a. Model

A complete simulation of this event is impossible because we have no data about the vertical distribution of water substances and the airflow pattern over the mountains. Then we will use several assumptions based on previous knowledge.

The model consists of two parts; Model 1 and Model 2. Model 1 is used to calculate the airflow pattern, while Model 2 calculates the distribution of the precipitating water. The equations in Model 1 are the same as those in the two-dimensional moist mountain-wave model constructed by Durran and Klemp (1982). The variables in Model 2 are the mixing ratios of water vapor (Q_v), cloud water (Q_c) and precipitating water (Q_p). The prognostic equations are given by:

$$\frac{\partial Q_v}{\partial t} = -u \frac{\partial Q_v}{\partial x} - (Gu + Hw) \frac{\partial Q_v}{\partial \zeta} - P1 + P2, \quad (1)$$

$$\frac{\partial Q_c}{\partial t} = -u \frac{\partial Q_c}{\partial x} - (Gu + Hw) \frac{\partial Q_c}{\partial \zeta} + P1 - P3 - P4, \quad (2)$$

$$\frac{\partial Q_p}{\partial t} = -u \frac{\partial Q_p}{\partial x} - (Gu + Hw) \frac{\partial Q_p}{\partial \zeta} + \frac{H}{\rho} \frac{\partial}{\partial \zeta} (\rho V p Q_p) - P2 + P3 + P4, \quad (3)$$

where G and H are the parameters for the transformation of the vertical coordinate (as in Durran and Klemp, 1982), ζ is the vertical coordinate and

Fig. 8. Distribution of the frequency of radar echoes stronger than level 3. The 37 radar-echo pictures produced every 15 minutes in Period 2 were used to count the frequency. The broken-line indicates the coast-line of the Ohsumi Peninsula. Locations of the rain-gauge stations A5, A8, B4 and C1 are denoted by black spots.

ρ is the density of the air. The symbols u and w represent the horizontal and the vertical wind velocity, which are given from the results of Model 1. The terminal velocity of precipitating particles, V_p , is formulated by Lin *et al.* (1983) as:

$$V_p = \frac{a\Gamma(4+b)}{6\lambda^b} \left(\frac{\rho_0}{\rho} \right)^{\frac{1}{2}}. \quad (4)$$

We assume that precipitating particles behave as snow crystals when the temperature is below 0°C and behave as raindrops when the temperature is above 0°C. The parameters a and b are given as $a = 1.139 \text{ m}^{1-b} \text{ s}^{-1}$ and $b = 0.11$ for snow crystals (Rutledge and Hobbs, 1983) and $a = 842 \text{ m}^{1-b} \text{ s}^{-1}$ and $b = 0.8$ for raindrops (Lin *et al.*, 1983). Γ is the gamma function and ρ_0 is the air density at the surface. The symbol λ is the parameter given by Lin *et al.* (1983).

$P1$, $P2$, $P3$ and $P4$ represent the transformation rate between water vapor and cloud water, the evaporation rate of precipitating water, the growth rate of precipitating water by accreting cloud water, and the autoconversion rate from cloud water to precipitating water, respectively. We used the formulation of Asai (1965) for $P1$, the formulations of Kessler (1969) for $P2$ and $P4$, and the formulation of Lin *et al.* (1983) for $P3$.

The important point in this simulation is how to represent the precipitation from the typhoon. Because we have no data about the vertical distribution of precipitating water, it is unknown which type of precipitating clouds produced the rainfall. However, following facts suggest the rainfall was mainly produced by stratiform clouds. First, the rainfall at Kagoshima City was relatively weak and continuous during Period 2 (Fig. 3). Second, the convectively unstable layer was restricted below the 850 hPa at 21 JST above Kagoshima City (Fig. 4). Third, the Ohsumi Peninsula had been covered with a weak and broad rainfall region in Period 2 (Fig. 2). Fourth, usually a stratiform precipitation exists between the eyewall and the rainband of a tropical cyclone (*e.g.* Jorgensen, 1984; Marks and Houze, 1987). A conceptual model of the stratiform precipitation within a tropical cyclone is proposed by Marks and Houze (1987). According to their model, the precipitating water is mainly produced by the condensation due to a mesoscale updraft above the melting layer. In the present simulation, the production of precipitating water by the mesoscale updraft is represented by inputting snow crystals into the "cloud layer" which lies between the 6 km and the 10 km level (Fig. 9b). We ignore the dynamic effect of the mesoscale updraft because it is considered to be small. The input rate of snow particles is 7 mm/h. This rate is similar to the rainfall intensity at Stations D1–D3, where the orographic effects

appeared to be small. The particles are inputted uniformly at every level in the cloud layer.

The results of Model 2 do not feed back to Model 1. Namely, we assume the distribution of precipitating water does not affect the airflow pattern. This assumption is acceptable when the mixing ratio of precipitating water is relatively small. We consider the assumption is not unrealistic in this case because stratiform precipitation does not produce strong flow in general. The effect of this assumption will be discussed in Section 4.

The size of the domain is 15 km in the vertical direction and 240 km in the horizontal direction (Fig. 9b). The horizontal mesh size is 2000 m and the vertical domain has 30 layers. We put a small mountain at the center of the domain whose shape is given by

$$Zs = \frac{hd^2}{x^2 + d^2}, \quad (5)$$

where Zs is the height of the ground, h ($= 800 \text{ m}$) is the height of the mountain peak and d ($= 2000 \text{ m}$) is the parameter which determines the mountain width. This represents the Kimotsuki mountains. In Model 1 the vertical profiles of θ (Fig. 4) and the southeastern wind component above Kagoshima City (Fig. 9a) is used for the initial condition. The wind velocity above the 10 km level is set to be constant. For simplicity the initial air is assumed to be saturated. Boundary conditions are the same as those in Durran and Klemp (1982). In Model 2 we used a cyclic condition at the lateral boundaries for Qp . Other boundary conditions are the same as Model 1. Prognostic equations of Model 1 and 2 are integrated until all the variables reach the steady state.

b. Computation cases

Table 2 describes the conditions in the computation cases. Five cases are made. In Case 1 all the production terms of precipitating water are set to be zero. In this case only the advection terms exist in (3). In Case 2 the accretion growth of precipitating water is imposed on Case 1. In Case 3 both the accretion growth and the evaporation of precipitating water are imposed. Case 4 is the control case in which all the production terms are active. We will evaluate the effects of advection, accretion growth, evaporation, and autoconversion by comparing the results in these cases.

In Cases 1–4 we used the fall speed given by Rutledge and Hobbs (1983) as the terminal velocity of snow crystals. In Case 5, as an extremely different case, we use the terminal velocity of raindrops for the fall speed of the snow crystals. The effects of the fall speed of snow crystals are examined in this case.

Fig. 9. (a) The horizontal wind profile used for the initial condition of Model 1. The wind velocity below the 10 km level is the southeastern wind component above Kagoshima City observed at 21 JST on 9 August, 1993. The wind velocity above the 10 km level is assumed to be constant. (b) The size of the domain, the shape of the mountain, the 0°C level and the cloud layer in the numerical model.

c. Results

Figure 10 shows the stream lines and the distribution of cloud water calculated by Model 1. In the layer below the 5 km level, an updraft exists above the upslope of the mountain. The water vapor condenses in the updraft and accumulates a large amount of cloud water over the crest. Above the 5 km level, the updraft is very weak on the windward side of the crest, while a strong downdraft exists on the lee side from $x = 0$ to 10 km. The downdraft is a part of the mountain waves generated by orographic forcing. From $x = 5$ km to 20 km, the air is unsaturated and no cloud water exists at all the level. This dry region was produced due to the adiabatic heating by the downdraft.

Figure 11 shows the horizontal variations of the rainfall intensity at the surface calculated by Model

2. In the control case (Case 4) the rainfall intensity is much larger than the inputted value (7 mm/h) from $x = 0$ to 45 km. Namely, the rainfall intensity in Case 4 is strongly enhanced on the lee side of the mountain, as observed on the Ohsumi Peninsula.

In Case 1 the production terms of precipitating water are excluded and the advection terms are isolated. In this case a strong intensity is found around $x = 30$ km. This indicates the advection of precipitating particles is one of the important factors which contributed to the rainfall enhancement in Case 4. Figure 12a shows the distribution of Qp in Case 1. There is a high Qp area below the 5 km level from $x = 0$ to $x = 30$ km. This area touches the surface around $x = 30$ km where a strong intensity was found. The formation of the high Qp area can be explained by the trajectories of the precipitat-

Table 2. Conditions for computation cases.

Case	Growth of precipitating water by accretion	Evaporation of precipitating water	Autoconversion from cloud water to precipitating water	Form of precipitating particles above the 0°C level
1	No	No	No	Snow
2	Yes	No	No	Snow
3	Yes	Yes	No	Snow
4	Yes	Yes	Yes	Snow
5	Yes	Yes	Yes	Rain

Fig. 10. Stream lines and the mixing ratio of cloud water calculated by Model 1. The vertical displacement of the stream lines is multiplied by 5 for display. Contours of cloud water are drawn every 0.2 g/kg.

ing particles shown in Fig. 12b. Particles L and M, which were inputted at the 7 km level, are only 10 km apart at the surface, yet they were separated by 22 km at the 7 km level. This indicates the particles approached each other in their falling process. The approach of the particles contributed to the formation of the high Q_p area. It should be noted that the two particles cross the 0°C level in a similar place around $x = 5$ km, where a strong downdraft exists. This suggests the downdraft transported the two particles below the 0°C level and made them close to each other.

The difference of the rainfall intensity between Case 1 and Case 2 indicates the effects of the accretion growth of precipitating water (Fig. 11). The intensity in Case 2 is much larger than that in Case 1 from $x = 0$ to $x = 20$ km. This suggests the accretion growth is also the important factor which contributed to the rainfall enhancement. The large intensity from $x = 0$ to 20 km in Case 2 results from the strong accretion of cloud water in the large Q_c area above the mountain (Fig. 10). Because the horizontal wind velocity is approximately four times as large as the fall speed of raindrops, the particles which passed through the large Q_c area fell around $x = 0$ to 20 km.

In Case 3 only the effect of autoconversion from cloud water to precipitating water is excluded from Case 4. The distribution of the rainfall intensity in Case 3 was very similar to that in Case 4 (Fig. 11). This indicates the effect of autoconversion was very small. On the other hand, the effect of evaporation is large on the lee side, as indicated by the difference between Case 2 and Case 3.

In Case 5 we used the terminal velocity of raindrops for the fall speed of snow crystals. This case shows smaller rainfall intensity than the other cases

Fig. 11. Horizontal variation of rainfall intensity at the surface in each computation case. The curve of Case 3 lies on that of Case 4.

around $x = 30$ km (Fig. 11). In this case the advection was not so effective as in Case 1–4. In Case 1–4, the heavy rainfall around $x = 30$ km was produced by the downdraft which transported snow crystals to the lower layer (Fig. 12). In Case 5, however, the downdraft did not transport so many crystals because their mixing ratio was very small above the 0°C level. The value of Q_p just above the 0°C level was only 0.5 g/kg in Case 5, while it was 3.8 g/kg in the other cases. The small Q_p in Case 5 is attributed to the large fall speed of crystals; namely, the inputted crystals fell so quickly that they did not accumulate above the 0°C level. In this situation the downdraft does not produce a heavy rainfall because it transports only a little amount of snow crystals.

Fig. 12. (a) Distribution of Qp in Case 1. Contours are drawn every 1.0 g/kg where $Qp > 1.0$ g/kg and 0.1 g/kg where $Qp < 1.0$ g/kg. (b) Trajectories of precipitating particles L and M (solid lines), distribution of w (thin dotted lines; contoured every 0.5 m/s) and the isotherm of 0°C (thick broken line) in Case 1.

4. Discussion

The numerical model simulated the heavy rainfall on the lee side of the Kimotsuki Mountains. However, the process shown in the simulation is not always the same as those in the real atmosphere, since we used many assumptions in the simulation. In this section we compare the results with the observation and discuss the rainfall increasing process over the Ohsumi Peninsula.

In the simulation, two different processes contributed to the rainfall enhancement. In the first process, the precipitating particles grew in the lower layer by accreting orographically produced cloud water. This process is known as the "seeder-feeder mechanism" (Bergeron, 1965). In the simulation this process had a large effect from the crest of the Kimotsuki Mountains to its 20 km lee. This region just corresponds to that where the heavy rainfall was observed during Period 2 (Fig. 5). This suggests the heavy rainfall can be explained by the seeder-feeder mechanism at least qualitatively. Moreover, strong echoes frequently appeared over the Kimotsuki Mountains (Fig. 8). This fact also suggests

the occurrence of the seeder-feeder mechanism. It is considered that the mechanism had a large effect in the formation of the heavy rainfall.

The other process is the local transport of snow particles by the mountain-wave downdraft (Case 1). This factor also made a considerable contribution to the rainfall enhancement in the simulation. However, we could not find any strong echo at the corresponding region where a large Qp was found in Case 1. This suggests the rainfall enhancement by this process could not be detected by the radar. However, it does not always imply the process did not act in this case, because the radar-echo intensity is classified very roughly in the data set.

The simulation showed two conditions are required for this process to have a large effect. First, a downdraft must exist around the 0°C level. In the simulation a downdraft of about 1 m/s was produced around the 0°C level. However, there is some uncertainty in this airflow calculation because the effects of loading and evaporation of precipitating water are neglected. In order to incorporate these effects, we introduced the equations (1)–(3) into Model 1 and

recalculated the airflow pattern (Fig. 13). The result indicates the pattern of the downdraft is not greatly changed by these effects (Compare Fig. 13 with Fig. 12b). It is considered that the atmospheric condition was favorable for the formation of the downdraft. As the second condition, a large amount of ice particles must exist just above the 0°C level. When the amount was very small, this process did not have a large effect because the downdraft transported only a small amount of ice particles (Case 5). In the control case, the mixing ratio of ice particles was 3.8 g/kg (corresponding to 2.5 g/m^3) just above the 0°C level. This value seems not to be unrealistic because it is in the range of the ice concentration near the center of a tropical cyclone measured by Houze *et al.* (1992).

Some previous observations suggest the downdraft of the mountain wave affects the precipitation. For example, Uttal *et al.* (1988) showed the particle habit in the downdraft region was different from that predicted on the basis of temperature. Recently Nakai and Endoh (1995) showed the radar-echo structure of snow clouds was modified on the lee side of the mountain where a downdraft prevailed. Although we could not obtain any observational evidence in this case, it is considered that the downdraft of the mountain wave also contributed to the heavy rainfall.

In the simulation the autoconversion from cloud water to precipitating water did not have large effects. This result is reasonable if we consider the wind speed and the mountain width in this case. When the wind speed is 30 m/s , the air parcel takes only 5.5 minutes to pass through the mountain whose width is about 10 km . This period is too short for cloud droplets to form a precipitating particle. Probably, the contribution of this process was very small in this case.

The upper air sounding at Kagoshima City (Fig. 4) indicates that convectively unstable layer existed near the surface. However, no cumulonimbus was produced in the simulation. We conducted the same simulation by using a finer mesh model (1 km horizontal grid), but the results were not changed. It is considered that the convectively unstable layer was too shallow to produce cumulonimbus.

In the present case heavy rainfall was observed on the lee side of the mountain. However, many previous observations reported that strong rainfall was observed on the windward rather than on the lee (*e.g.* Sakakibara and Takeda, 1973; Harimaya *et al.*, 1988). It is considered that the following three conditions were effective in this case to produce heavy rainfall on the lee side. First, the atmosphere was so moist that evaporation of raindrops was not strong in the lee-side dry region. Second, the wind was so strong that many cloud droplets could reach near the lee side before they were washed out by precipitating particles. Third, the moist air and the strong wind persisted for long time because of the slow movement of the typhoon (Fig. 2). However, we need more observations to make clear the favorable condition for the occurrence of the heavy rainfall on the lee side.

The present simulation could not reproduce the extremely heavy rainfall around Station A5. Because the extreme rainfall was concentrated around A5 (Fig. 5), it is considered the three-dimensional effect of mountains (Mass, 1981) would act there. We must use a three-dimensional model to simulate the more detailed features of this event.

5. Summary

The heavy rainfall over the Ohsumi Peninsula caused by the passage of Typhoon 9307 was studied with the use of the observation data and two-

Fig. 13. Distribution of w calculated by the model in which the effects of precipitating water is incorporated.

dimensional numerical simulations. The results are summarized as follows:

- (1) The heavy rainfall mainly occurred under the region between the eyewall and the rainband of Typhoon 9307.
- (2) The rainfall amount was much larger on the lee side of the mountains than on the windward side. The 9-hour rainfall exceeded 150 mm at the greater of the stations on the lee side, while it was only 80 mm on the windward side.
- (3) All the land-slide disasters occurred on the lee side of the mountains.
- (4) The rainfall enhancement on the lee side can be explained by the "seeder-feeder mechanism", in which the precipitating particles seeded from the typhoon grow by accreting cloud water formed by the orographic updraft. The particles grown over the mountains were carried to the lee side by the strong wind.
- (5) It is also suggested that the transport of snow particles by the mountain-wave downdraft made a contribution to the rainfall increment on the lee side.

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台風9307の通過によって、大隅半島に発生した豪雨の解析

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1993年8月9日の夜、台風9307が日本の南部に接近し、大隅半島に多数の土砂災害を伴う豪雨を発生させた。この豪雨の興味深い特徴は、降水量が山脈の風下側で著しく多かったことである。山脈風上側の観測地点では9時間雨量が80 mmであったのに対して、風下側では大部分の観測地点で150 mmを超えた。また、すべての土砂災害は山脈の風下側に発生した。この豪雨は、主として台風の眼の壁雲とレインバンドの間の領域でおこった。豪雨の期間中、山脈の上層に強いレーダーエコーが頻繁に出現した。

山脈の風下側で降水量が増加する過程を、2次元モデルによる数値シミュレーションで調べた。シミュレーションの結果は、降雨が主としてシーダ・フィーダ機構によって強められていたことを示した。すなわち、上層の雲から落ちてきた降水粒子が、地形性上昇流によって形成された雲粒を捕捉することによって成長し、山脈上で成長した粒子が、台風に伴う強い風によって風下側に運ばれたと考えられる。また別の機構として、山岳波に伴う下降流が、局所的に多量の雪粒子を下層に運ぶことも、風下側の降雨量の増加に寄与していたと考えられる。