A General View of the Structure of Typhoon 8514

Observed by Dual-Doppler Radar

—From Outer Rainbands to Eyewall Clouds—

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(Manuscript received 10 July 1991, in revised form 8 July 1992)

Abstract

The structure of the rainbands and eyewall of Typhoon 8514, which landed at the central region of Japan on 30 August 1985 was observed by two ground-based Doppler radars. The main purpose of the present study is to describe a general view of the structure of the typhoon using data of the dual-Doppler radar.

Although the typhoon was a small and weak typhoon, it retained the characteristics of tropical cyclones: it was accompanied by spiral rainbands (an outer rainband and an inner rainband) and had a warm core in its upper part.

The outer rainband was a spiral band located about 150 km from the center of the typhoon. This rainband consisted of continuous stratiform clouds and scattered convective clouds. A radar “bright band” was observed in this rainband. Wind perturbation induced by cooling-by-melting was observed just below the bright band. An updraft of 1.5 ms^{-1} was produced, mainly owing to the convergence of a southeasterly flow on the inner edge of the outer rainband. This updraft maintained the outer rainband.

The inner rainband was a convective spiral band located ~ 60 km from the typhoon center. The distribution of reflectivity and vertical velocity of this rainband indicated that an old echo cell existed in the inner part, while young echo cells existed in the outer part of this rainband. An inflow (the airflow toward the typhoon center) was observed in the lower layers of the inner rainband. This inflow reached the inner edge of the young cells, and produced an updraft there. When the depth of this inflow layer became thinner, the inner rainband decayed. This indicates that the inflow had an important role to play in maintaining the inner rainband.

Because the flow into the eyewall of the typhoon in the lower layers was weak, the radius of maximum wind (RMW) was located at the outer side of the axis of reflectivity maxima. The eyewall decayed when it moved to the inner area (nearer the typhoon center) of the RMW, where downdraft was predominant.

1. Introduction

Before the 1980s, the structure of the eyewall and rainbands of tropical cyclones was studied using data collected mainly by aircraft and conventional radars. (*e.g.*, Wexler, 1947; Gentry, 1964; Shea and Gray, 1973; Frank, 1984; Willoughby *et al.*, 1984b; Jorgensen, 1984a, b).

In the 1980s, using airborne Doppler radars, the three-dimensional and fine structures of tropical cyclones were revealed (Jorgensen and Marks, 1984; Marks and Houze, 1984, 1987; Barnes *et al.*, 1991). The airborne Doppler radar is demonstrated to be a powerful instrument for the observation of tropical

cyclones. However, since the pseudo-dual Doppler method is used to derive the horizontal wind from airborne Doppler radar data, one scanning sequence needs too much time to document the time evolution of the wind field of the eyewall and rainbands of tropical cyclones.

Ground-based Doppler radars are also used in studies of the structure of tropical cyclones. Sakakibara *et al.* (1985) and Ishihara *et al.* (1986) studied the structure of the rainbands of tropical cyclones around the Kanto district of Japan. Bluestein and Hazen (1989) analysed three types of precipitation areas of Hurricane Alicia. Jou (1991) studied the structure of the inner core of Typhoon Yancy. Lee and Tsai (1991) analysed topographic effects on a

typhoon. The general structure of typhoons, however, has not been studied yet.

Willoughby *et al.* (1984b) named the prominent spiral rainbands in hurricanes the “principal band”, the “connecting band”, and the “secondary bands”. The present paper will discuss the structure of two kinds of spiral rainbands and the eyewall of T8514. Spiral rainbands are classified into outer rainbands and inner rainbands according to the distance from the storm center. The outer rainband is similar to the principal rainband in Willoughby *et al.* (1984b); that is, it was made up of cellular convection in its inner part (near the typhoon center), and stratiform clouds in its outer part (far from the typhoon center). The inner rainband was a narrow (~ 10 km in width) convective spiral rainband which existed on the concave side of the outer rainband and was similar to the secondary bands in Willoughby *et al.* (1984b). The connecting band was not observed in T8514.

The objective of this paper is to describe a general view of the structure of Typhoon 8514 (T8514) which passed between our two Doppler radar sites on 31 August 1985. This is the first case that the center of a typhoon passed between two ground-based Doppler radars anywhere in the world and that continuous observation of outer rainbands, inner rainbands, and the eyewall of T8514 was carried out for the time evolution.

The following are the main subjects discussed in this paper:

- 1) The fine structure of the outer rainband, the inner rainband, and the eyewall of T8514.
- 2) The mechanism of development and decay of the inner rainband of T8514.
- 3) The features and behavior of the eyewall.

2. Data and procedure for analysis

In this study, two Doppler radars were operated by the research group of the Meteorological Research Institute (MRI). The characteristics of the 3 cm and 5 cm Doppler radars are given by Sakakibara *et al.* (1985). The 5 cm Doppler radar was located at MRI in Tsukuba and the 3 cm radar was located at ~ 28 km west-southwest of MRI (Fig. 1).

The observational procedure and data analysis are the same as those of Ishihara *et al.* (1986) except for the heights of the analysis levels. Outline of analysis procedure is as follows:

1) Observed Doppler velocity and reflectivity in spherical coordinates are interpolated into a three-dimensional Cartesian grid using the weighted-mean interpolation method. The weighting function is in inverse proportion to the square of the distance from the data point to the grid point. The horizontal grid spacing is 0.785 km.

2) The three-dimensional components of air velocity are deduced by integrating the anelastic equation of continuity upward from the lower boundary.

Fig. 1. Track and central pressure of Typhoon 8514. Solid triangles indicate the sites of the 3 cm and 5 cm Doppler radars.

The boundary condition is $w=0 \text{ ms}^{-1}$ at the lower boundary.

3) Volume-mean terminal fall speed of precipitation particles, V_t , with correction for air density (Foote and du Toit, 1969) is estimated from the radar reflectivity Z (Rogers, 1964) observed by the 5 cm radar as

$$V_t = -3.8 \left(\frac{\rho_0}{\rho} \right)^{0.4} Z^{0.0714} \quad (1)$$

where ρ_0 and ρ are air density at the surface and the grid point, respectively.

The winds derived from dual Doppler radar analysis contain errors from several sources. Some of them are: (1) geometric arrangement of two radars (2) radar echoes' advection during the data sampling period (3) errors of estimate of the terminal fall speed of precipitation particles caused by attenuated reflectivity (4) errors in vertical velocity derived by integrating the continuity equation.

Lhermitte and Miller (1970) derived relation of error variances of Doppler velocity and those of u , v component of horizontal winds:

$$\frac{\sigma_u^2 + \sigma_v^2}{\sigma_1^2 + \sigma_2^2} = \text{cosec} 2\beta \equiv b. \quad (2)$$

Fig. 2. Synoptic charts at the sea level (a) and at the 500-hPa level (b) for 21 JST on August 30, 1985. Solid lines in (a) represent sea-level pressure (hPa). Solid and dashed lines in (b) represent geopotential height ($\times 10$ m) and temperature ($^{\circ}\text{C}$), respectively.

In this equation, σ_1^2 , σ_2^2 , σ_u^2 , σ_v^2 are the variances of Doppler velocity of two radars and u , v components, respectively. β is angle of inter-beams. Applying this relation to our analytic domain, we obtained that “ b ” is less than 4. The value of $\sigma_1^2 + \sigma_2^2$ in this case was estimated as $\sim 0.3 \text{ ms}^{-1}$ using the formula obtained by Doviak *et al.* (1976). The geometric arrangement of the radars and variances of Doppler velocity suggest that the horizontal winds were estimated accurately.

The advection of radar echoes during data sampling was large. We corrected this effect using the method developed by Gal-Chen (1982).

The effect of attenuation on the estimate of the terminal velocity of precipitation is evaluated as follows. Observed rainbands were 10–20 km in width and the observed maximum reflectivity was 42.5 dBZ. Using a Z - R relation of $Z = 200R^{1.6}$, the maximum rainfall intensity in the rainband was estimated to be $\sim 16.5 \text{ mmh}^{-1}$. If we assume that rainfall of 16.5 mmh^{-1} existed for 20 km between the radar and target area, the radar wave attenuation caused by the precipitation particles is estimated as ~ 1 dB by using an attenuation constant of $K_R = 0.0022R^{1.17}$ (dB/km) (Gunn and East, 1954). This attenuation induces an error of only $\sim 10 \text{ cms}^{-1}$ in estimates of terminal fall speed of precipitation particles.

The above-mentioned error evaluation indicates that the error sources (1)–(3) have only minor effects on analysed results.

Since the upward integration scheme is used to deduce the air velocity in this study, the estimate of the error in vertical air velocity increases with

increasing height. The accuracy of the vertical air velocity, however, was satisfactory up to the top of the figures in this paper.

Doppler radar observations were made at the following nine antenna elevation angles: 1.2° , 2.6° , 4.6° , 7.2° , 10.4° , 14.4° , 19.4° , 25.4° , and 32.4° . The vertical resolution of radar data at the range of the rainbands was between ~ 200 m and ~ 2300 m. Thus, concentric configurations sometimes appear in the distribution of reflectivity at altitudes above the 5 km level because of insufficient vertical resolution.

Barnes *et al.* (1983) and Ishihara *et al.* (1986) defined the rainbands as the areas with reflectivity exceeding 25 dBZ and 30 dBZ, respectively. Since relatively high reflectivity areas were observed in T8514, to indicate the position of the rainbands clearly, the areas with reflectivity exceeding 35 dBZ are defined as the rainbands in this study.

The following terminology is used in this paper: (1) an inflow is the component of air flow toward the storm center; (2) an outflow is the component of air flow away from the storm center.

3. Large-scale features of the typhoon

Figure 1 shows the track and the central pressure of T8514. The position of the typhoon center and the central pressure was reported by the Japan Meteorological Agency (JMA) based on aircraft and surface observations. The typhoon moved northwestward at first. Then the direction of movement changed to northeastward on the night of 30 August. The typhoon landed at 2300 JST (Japan Standard Time, UTC + 9h) on 30 August and passed through

our observation domain around 0200 JST on 31 August.

Figure 2 shows the synoptic charts for the surface and the 500-hPa level at 21 JST on August 30, when the center of the typhoon was ~ 150 km south-southwest of Tsukuba. The central pressure of the typhoon was 992 hPa, and the radius of the 1000 hPa isobar was ~ 30 km. These indicate that the typhoon was a small and weak one. Two other typhoons were observed southwest of T8514. The temperature field around T8514 at the 500-hPa level was uniform. A baroclinic zone is seen north of 45°N in the synoptic chart at 500-hPa. Moreover, a warm core was found above the 400-hPa level at the typhoon center in synoptic charts (not shown). That is, air warmer than the surrounding air by $\sim 2^\circ\text{C}$ was observed in the vicinity of the typhoon center above the 400-hPa level. Typhoons generally change their characteristics from tropical cyclones to extra-tropical cyclones in mid-latitudes near Japan (Muramatsu, 1982). These observations, however, suggest that T8514 retained the characteristics of a tropical cyclone during its passage over Tsukuba, though it was small and weak.

The distributions of radar reflectivity observed by a conventional radar (10 cm) at Mt. Fuji from 1938 JST on 30 August to 0100 JST on 31 August are shown in Fig. 3. The center of the typhoon was located at ~ 180 km south-southwest of Tsukuba at 1938 JST on 30 August. The eye of the typhoon is visible as a clear area ~ 70 km in diameter. A large band-shaped radar echo extended from north of the storm center, through east of the center and extended south of it. An outer rainband of T8514 examined in the next section existed in the northern part of this radar echo. We first observed the wind field of the outer part of the outer rainband. The typhoon moved northward and landed at 2300 JST on 30 August, when the eye of the typhoon became smaller than ~ 10 km in diameter. We can see an arc-shaped rainband south of Tsukuba at 2346 JST on 30 August, which extended from west to east. This is an inner rainband of the typhoon. An intense radar echo exceeding 35 dBZ was observed east of the typhoon center at 0100 JST on 31 August. This radar echo was the eyewall of the typhoon.

One-minute rainfall amounts were measured by a rainfall intensity meter. The time change of rainfall intensity at Tsukuba is shown in Fig. 4. This figure indicates that three major rainfall events were observed at Tsukuba. Echo patterns by the conventional radar at Mt. Fuji (Fig. 3) showed that the first major rainfall was from the outer rainband (RO), the earlier part of the second major rainfall was from the inner rainband (RI), and that the latter part and the third major rainfall event were caused by the eyewall clouds.

The first of the major rainfall events was observed

Fig. 3. Distribution of radar reflectivity observed by the Mt. Fuji radar. Contours of 5 dBZ and 35 dBZ are drawn. Areas in excess of 35 dBZ are cross-hatched. Doppler analysis domains in Figs. 6, 11, 12 and 16 are indicated and labeled with analysis time.

Fig. 4. Record of the rainfall intensity meter at Tsukuba.

from 2000 JST to 2300 JST on 30 August. The radar echo structure in Fig. 3 shows that the rainfall maximum was caused by the outer rainband (RO). There were several peaks of $15\text{--}30\text{ mmh}^{-1}$ in relatively uniform rainfall of $6\text{--}7\text{ mmh}^{-1}$ from 2000 JST to 2130 JST. Since the northern part of the outer rainband passed Tsukuba during this period, this time change of rainfall intensity suggests that a wide stratiform cloud and scattered weak

Fig. 5. Vertical profiles of equivalent potential temperature (θ_e) and saturation equivalent potential temperature (θ_s^*) at 2030 JST on August 30 (solid lines) and 0230 JST on August 31 (dashed lines) at Tsukuba. Vertical wind profiles are also indicated. The wind plotting convention is: flag, 50 knots and barb, 10 knots. The low-temperature layer produced by cooling-by-melting was observed at 2030 JST is shaded.

convective clouds coexisted in that part. Two intense rainfall maxima ($60\text{--}80\text{ mmh}^{-1}$) were observed from 2130 JST to 2240 JST, while the southern part of the outer rainband passed over Tsukuba. Thus, strong convective clouds existed in this part of the rainband. Powell (1990) found that outer hurricane rainbands consist of cellular echoes on the inner portion (the portion of the rainband near the hurricane center) of the rainband and stratiform cloud is predominant in the outer portion of it. The outer rainband of T8514 had a similar structure to that of the "principal band" and Powell's outer band.

Another major rainfall maximum was observed from 0000 JST to 0220 JST on 31 August. The earlier part of this rainfall up to 0100 JST was caused by the inner rainband (RI).

The latter part after 0100 JST and the third large rainfall intensity event up to 0400 JST on 31 August, was caused by the eyewall of the typhoon (RE). Since the eye of the typhoon passed near Tsukuba, light rain was observed around 02 JST on 31 August.

Figure 5 shows the vertical profile of equivalent potential temperature, saturation equivalent potential temperature, and horizontal winds observed at 2030 JST on 30 August and at 0230 JST on 31 August at Tsukuba. A convective instability layer was

seen from the surface to 820 hPa at 2030 JST, when the outer rainband existed just south of Tsukuba. A dry and stable layer was observed through the 750–600 hPa layer. Since warm and moist air was transported to middle levels by 0230 JST on 31 August when the typhoon center had already passed near Tsukuba, stable stratification was observed throughout the troposphere.

Southeasterly winds were observed from the surface to the 300-hPa level except just below the freezing level at 2030 JST on 30 August. Backing of the wind direction of $\sim 40^\circ$ was observed just below the freezing level at 4.7 km. The wind direction changed to southwesterly and the wind velocity became stronger in the lower levels at 0230 JST on 31 August.

4. Results

4.1 Structure of the outer rainband

The outer rainband, which was oriented west to east, was located ~ 150 km north of the storm center. One of the features of the outer rainband is that the crossing angle to circles about the typhoon center was large, $\sim 40^\circ$. A part of the outer rainband of T8514, which mostly consisted of stratiform cloud, passed over the domain of dual Doppler radar observation from 1900 JST to 2000 JST on 30 August.

Figure 6 shows the distribution of radar reflectivity and horizontal wind in the outer rainband. The width of the rainband was ~ 20 km and its orientation was west to east. The distribution of radar reflectivity was not uniform in the rainband and there were several high-reflectivity areas with reflectivity exceeding 37.5 dBZ at the 1 km level. At the 2 and 3 km levels a lower reflectivity was observed near the center of the rainband than in the other parts. Large regions with high reflectivity exceeding 40 dBZ were found at the 4 km level. Moreover, reflectivity at the 5 km level was higher than at the 2 and 3 km levels. The following two facts indicate that the high-reflectivity areas at the 4 and 5 km levels are the radar "bright band". One is that the freezing level was at 4.7 km altitude in the sounding at 2030 JST on 30 August at Tsukuba (see Fig. 5). The other is that a high reflectivity area at ~ 4.5 km height was found in the vertical cross section of the rainband in Fig. 7. In addition, a rather convective echo area exceeding 37.5 dBZ was found from the base of the radar beam to the 3 km level on the southern edge of the rainband (Fig. 7). These facts indicate that this rainband was stratiform with a rather weak convective echo embedded in it.

A concentric configuration can be seen in the distribution of the reflectivity above 5 km levels because of insufficient vertical resolution.

A nearly uniform southeasterly wind blew into the rainband at the 1 km level (Fig. 6). A maximum wind of 35 ms^{-1} was observed in the southwestern

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Fig. 6. Horizontal sections of reflectivity and horizontal winds at 1938 JST on August 30, 1985. Contours of reflectivity are drawn from 15 dBZ at intervals of 2.5 dBZ. Areas in excess of 35 dBZ are shaded. The ordinates and abscissa are range in the north-south and west-east directions, respectively. A dot-dashed line AB indicates the position of the vertical cross-section in Fig. 7. A parallelogram NS indicates the position of the composite vertical cross section in Fig. 9. Squares indicate the locations of the two Doppler radars. The ground-relative motion of the rainband, 'SYSTEM', and the effective position of RHI in Fig. 10 shown by a solid line CD are also shown.

Fig. 7. Vertical cross-section (AB in Fig. 6) of the outer rainband. Contours of reflectivity are drawn from 15 dBZ at intervals of 5 dB. Areas in excess of 35 dBZ are shaded.

part of the rainband. A similar wind field can be seen at the 2 to 3 km levels. However, the wind field at the 4 to 5 km levels changed substantially. At these levels, the wind direction changed to easterly near the rainband. At the 6 km level the wind direction returned to southeast. Thus, a perturbed wind field was present between the 4 and 5 km layers in the rainband. A similar wind profile was also observed in the sounding at 2030 JST on 30 August at Tsukuba (Fig. 5). Backing of wind direction, from southeast to east-northeast, was found in a layer of 400 m depth just below the freezing level. These observations indicate that wind field perturbation is related to the "bright band". We will discuss this mechanism later.

Except for the "bright band" layer, the wind blew from the inner side (nearer to the typhoon center) to the rainband. At the surface, however, an east to east-northeast wind was observed (Fig. 8). Thus, only a weak ground-relative inflow from the outer side of the rainband toward the typhoon center was found near the surface. South-easterly winds observed above the 1 km level were also observed at Mt. Tsukuba (868 m above sea level) which is located 30 km north of the rainband. These observations suggest that ground-relative inflow to the storm center in the outer rainband occurred in a very thin layer.

Figure 9 shows a composite (averaged) of six vertical cross-sections of the central part of the rainband which is normal to the rainband at 1938 JST. The position of the cross section is indicated by the parallelogram in Fig. 6. The scale of the rainband was ~ 15 km in width. At the 8–10 km range, a high-reflectivity area, exceeding 37.5 dBZ, was found at the 1 km level in Fig. 9a. This corresponds to the convective echo in Fig. 7. The high-reflectivity area in Fig. 9a was depicted as a thin layer owing to smoothing of the data. Other regions exceeding 37.5

Fig. 8. Horizontal section of reflectivity and eddy horizontal winds at the 1 km level at 1938 JST and surface ten-minutes-averaged wind observed at 1940 JST. Eddy horizontal winds are derived by subtracting the mean wind vector of the 1 km level from the horizontal winds. Contours and shading are the same as in Fig. 6. The surface wind plotting convention of barb is 2 ms^{-1} .

dBZ were observed at the 4 km level at the 8–10 km range and at the 15 km range. These regions are considered to be the "bright band" as shown in Fig. 7. The depth of the "bright band" is depicted as relatively large owing to our data interpolation method in this figure.

The wind data shown in Figs. 9b–9c are band-relative winds which were derived by subtracting movement of the outer rainband (318° , $\sim 15 \text{ ms}^{-1}$) from the observed winds.

Figure 9b shows the band-relative normal component of winds V_n' . A low-level inflow of 2 ms^{-1} was found outside of the 20 km range. At the 20 km range, the inflow changed to outflow. Although an updraft existed at this range, only a weak echo was found. A maximum relative outflow of 4 ms^{-1} was found on the inner edge (southern edge) of the rainband at 2 km height. Above 3 km, a strong band-relative inflow was observed. This is due to the above-mentioned wind perturbation near the "bright band".

Figure 9c shows the band-relative tangential wind component, V_t' . A maximum V_t' of 17 ms^{-1} was found on the inner edge of the rainband at the 1 km level. A small deficit of surface pressure (~ 0.7 hPa) was observed near the southern edge of the rainband (not shown). Because this pressure deficit

Fig. 9. Composite vertical cross-sections of the outer rainband (NS in Fig. 6), (a) reflectivity, (b) normal component of band-relative wind Vn' , (c) tangential component of band-relative wind Vt' , (d) vertical velocity. Contours of reflectivity are drawn from 10 dBZ at intervals of 2.5 dB. Areas in excess of 35 dBZ are shaded. Contours of Vn' and Vt' are drawn at every 1 ms^{-1} . Positive areas are shaded. A positive value of Vn' indicates outflow from the storm-center side, and that of Vt' the cyclonic component. Contours of vertical velocity are drawn every 0.5 ms^{-1} . Positive areas are shaded.

Fig. 10. RHI of the outer rainband at 1910 JST on 30 August 1985. Contours of reflectivity are drawn from 5 dBZ at intervals of 5 dB. Areas with reflectivity higher than 35 dBZ are shaded.

may accelerate the southeasterly wind there, a large Vt' was observed. In the rainband, the band-relative tangential component Vt' is nearly uniform; the vertical change of Vt' was as small as 1 ms^{-1} .

Vertical velocity is shown in Fig. 9d. An updraft of 1.5 ms^{-1} was present on the inner edge of the rainband. This position coincided with the rather convective echo area in Fig. 7. The eddy wind field at 1 km indicated that convergence occurred due to the deceleration of wind speed on the inner edge of the rainband (Fig. 8). A downdraft of 3 ms^{-1} existed at the 15 km range, where an overhang of the area, exceeding 35 dBZ, was observed at the 4 km level (Fig. 9a). Another feature is that a weak updraft of 0.5 ms^{-1} was found at the center of the rainband. A prominent "bright band" was found at this area in Fig. 7.

The RHI pattern of the northwest part of the rainband at 1910 JST revealed that the echo top of the rainband was higher with increasing distance from the storm center (Fig. 10). A "bright band" was observed through 4 to 5 km altitude. These features suggest that a mesoscale updraft existed above the bright band.

Shallow convective echoes and elevated echo were observed at the $\sim 11 \text{ km}$ range (Fig. 10).

4.2 Structure and evolution of the inner rainband

Typhoon 8514 landed at 2300 JST on 30 August. After the landfall, a rainband oriented west to east formed 60 km north of the typhoon center. This rainband was the inner rainband of T8514. The crossing angle (to circles about the typhoon center) of the inner rainband was small, being $\sim 10^\circ$.

Figures 11 and 12 show the time evolution of the distributions of reflectivity and eddy wind fields. We examine the features of wind fields such as convergence and divergence from the eddy wind fields.

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Fig. 11. Horizontal sections of reflectivity and eddy horizontal winds at 2329 JST on 30 August. Contours and shadings are the same as in Fig. 6. A parallelogram indicates the position of the composite vertical cross-section in Fig. 13. A dot-dashed line indicates the position of the vertical cross-section in Fig. 15. Mean wind vectors at each level are indicated at the right bottom of the figures. Eddy wind fields are derived by subtracting the mean wind vector of each level from the horizontal wind.

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Fig. 12. As in Fig. 11, but for 2346 JST on 30 August. A parallelogram indicates position of the composite vertical cross section in Fig. 14. A dot-dashed line indicates the position of the vertical cross-section in Fig. 15.

The size of the inner rainband (RIN) was ~ 10 km in width and ~ 55 km in length at 2329 JST (Fig. 11). A core is defined as the local maximum of reflectivity exceeding 37.5 dBZ in this paper. Cores exceeding 40 dBZ were observed in the western part of the RIN at the 1 km level. Two smaller-scale rainbands A, B (RA, RB) which were oriented west to east were embedded in the central part of the RIN. Reflectivity in the western part of the RIN became lower with increasing height. In the eastern part, however, cores exceeding 40 dBZ were observed in the central part of the RB at 4 km. In the RHI pattern, which was obtained at 2304 JST (not shown), the vertical reflectivity gradient was weak and the

bright band was not observed in the RB. These indicate that the strong echo observed at the 4 km level was convective and in its growing stage.

The RA did not have a line structure at 2 km and almost disappeared at the 4 km level. This reflectivity pattern suggests that the RA was in its decaying stage.

High-reflectivity regions exceeding 40 dBZ at the 1 km and 2 km levels were much wider at 2346 JST than at 2329 JST (Fig. 12). At the 4 km level, high reflectivity regions exceeding 40 dBZ were not found, and reflectivity was much lower at this time than at 2329 JST. It is inferred that this descent of reflectivity cores was due to falling of large precipitation

Fig. 13. Composite vertical cross-section of the inner rainband at 2329 JST on 30 August, 1985; (a) reflectivity, (b) normal component of band-relative wind Vn' , (c) tangential component of band-relative wind Vt' , (d) vertical velocity. Contours and shadings are the same as in Fig. 9.

particles to lower levels. Thus, the RIN passed its mature stage and was in its decaying stage.

The wind field in the vicinity of the inner rainband contained cyclonic circulation. Thus mean wind vectors were almost the same as wind vectors around the central part of the inner rainband. By subtracting the mean wind vectors, a northerly wind perturbation was found at the western part of the rainband and a southerly wind perturbation was found at the eastern part as shown in Fig. 11.

A feature of the eddy wind field at 2329 JST was that strong southeasterly winds were present at the inner part (southern part) of the rainband at the 1 km level. Convergence occurred owing to a large decrease of wind speed on the inner edge of the RB. Eddy southeasterly winds were not found in northern part of the rainband, where a divergent wind field existed. Although a similar wind field could be seen at the 2 km level, eddy southeasterly winds at this level were weaker than at 1 km. Cyclonic flow was well defined at the inner part of the rainband at 4 km height. The ground-relative wind field (not shown) was southeasterly at all heights. Namely, ground-relative outflow from the storm center side was present at all levels above 1 km and no ground-relative inflow to the storm center was found.

The surface wind (not shown), however, was east-northeasterly. Therefore, surface air blew into the

rainband from the outer side (far side from the typhoon center). These facts indicate that the depth of ground-relative inflow was less than 1 km from the surface.

The eddy wind field observed at 2346 JST is depicted in Fig. 12. We can easily see the feature that strong southeasterly winds, which were found at 2329 JST at the 1 km level, had already disappeared at this time. The distribution of the horizontal divergence (not shown) indicates that divergence areas existed on the inner edge ($X=29-45$ km, $Y=18-23$ km) of the rainband. Southerly wind components decreased and northerly wind components increased around the outer part of the rainband at 1 km. Divergence on the inner edge of the rainband was not well defined at the 2 km level. Distinct cyclonic flow can be seen at 4 km height.

Figure 13 shows the vertical structure of the inner rainband around the central region, which is indicated by averaging over the width of a parallelogram in Fig. 11. The wind data which are shown in Figs. 13b and 13c are band-relative winds which were derived by subtracting the movement of the inner rainband (14° , $\sim 11.5 \text{ ms}^{-1}$) from the observed winds. Corresponding to RA and RB in Fig. 11, two reflectivity cores A and B can be seen in the inner rainband in Fig. 13a. The major core B was at 10–15 km range, in which a high-reflectivity area exceed-

Fig. 14. As in Fig. 13, but for 2346 JST.

ing 37.5 dBZ reached the 5 km level. The size of the core was nearly constant from the 1 km level to the 5 km level and this suggests that active convection produced this core. The other core, A, was shallow and was located at the 7 km range.

Figure 13b is the component of band-relative wind normal to the rainband, V_n' . Positive values are the southerly component, flowing from the typhoon center. The most noticeable feature is that there existed inflow with a maximum speed of 3 ms^{-1} below ~ 1.5 km height, and this inflow layer extended to the inner edge of core B. Thus, convergence was induced on the inner edge of core B at the 1 km level due to decreasing inflow (not shown). Maximum outflow was found at 3 km height at the inner edge of the rainband.

Figure 13c shows the band-relative tangential wind component, V_t' . The maximum V_t' was located at the inner edge of the rainband. V_t' changed substantially with height in the inner rainband; that is, it was 31 ms^{-1} at 1 km altitude, and 19 ms^{-1} at 6 km altitude. This indicates that the inner band was located in a highly sheared environment. Since the air of the low-level inflow had large angular momentum, a large V_t' occurred in the lower layer. This caused a large vertical change of V_t' .

Figure 13d shows the vertical velocity. Since a downdraft prevailed in the core A, this was in its decaying stage. On the other hand, an updraft was present at the inner edge of core B. This updraft at-

tained its maximum of 3 ms^{-1} at 5 km height. This structure suggests that the outer part of the RIN was developing, while its inner part was decaying.

Another feature of the vertical velocity was that a wave of wavelength $\sim 8 \text{ km}$ was present from the range 9 km to 39 km (Fig. 13d). A gravity wave is often observed within typhoon rainbands (*e.g.* Matsumoto and Okamura, 1985). Thus the wave in this figure was possibly the gravity wave induced by the up/downdrafts in the high-reflectivity area of the rainband and propagated outside of it. However, no other data which show the characteristics of this wave were obtained, and the nature of this wave remains obscure.

The vertical structure of the rainband at 2346 JST is shown in Fig. 14. A reflectivity core was present between the 15–20 km range at the 1 km level in Fig. 14a. Its maximum reflectivity exceeded 40 dBZ. Although the size of the core at this level was larger at this time than at 2329 JST, the height of the top of the core was lower. These features suggest that raindrops grew during their descent to lower layers. Another feature is that an echo-free area existed on the inner side of the rainband. Although a weak echo was observed below 3 km, no radar echoes were observed between the 0–10 km range above this level. The echo-free area expanded after the rainband made landfall. This area was probably caused by evaporation of precipitation particles in downdrafts.

Fig. 15. Vertical cross-section of the inner rainband along a dot-dash line in Figs. 11–12 made from only the 5 cm radar data. (a) reflectivity at 2329 JST on 30 August, (b) band-relative Doppler velocity at 2329 JST on 30 August, (c) as in Fig. 15(a), but for 2346 JST, (d) as in Fig. 15(b), but for 2346 JST. Contours of reflectivity are drawn from 15 dBZ at intervals of 5 dB. Areas exceeding 35 dBZ are shaded. Contours of Doppler velocity are drawn every 2 ms^{-1} . Positive values are shaded.

Figure 14b shows the distribution of V_n' . Very weak low-level inflow from the outer part of the rainband was observed outside the 30 km range. Another low-level inflow was present at the inner edge of the rainband at 1 km altitude, which caused divergence there. Outflow was strongest on the inner edge of the rainband at 3 km altitude and was weak on the outside of the rainband.

The distribution of V_t' is shown in Fig. 14c. The pattern of V_t' was similar to that at 2329 JST. A strong V_t' , however, was found in the outer part of the rainband above the 2 km level. A relative inflow layer existed around the 3 km level in Fig. 14b. A large value of V_t' was produced there because the angular momentum of inflow air was large.

The vertical velocity is shown in Fig. 14d. A striking feature is that a strong downdraft of 3.0 ms^{-1} was present on the inner edge of the rainband. The existence of this strong downdraft coincides with the fact that radar reflectivity is weak above 3 km height on the inner side of the rainband. An updraft existed above 4 km height at the $\sim 17 \text{ km}$ range. These vertical velocity patterns suggest that the inner rainband had passed its mature stage. A wave which was similar to that found in Fig. 13d also existed between the range 20 km and 30 km.

To examine the wind field below the 1 km level, which cannot be obtained from the dual Doppler

radar observation, vertical cross sections were made using only the 5 cm radar data (Fig. 15). The position of the vertical cross section is indicated by the dot-dashed line in Figs. 11–12. Band-relative inflow of maximum value $\sim 14 \text{ ms}^{-1}$ was found near the ground at 2329 JST. The depth of the inflow layer became $\sim 900 \text{ m}$ at 2346 JST. This is consistent with the fact that a relative inflow was observed in very limited areas above the 1 km level in Fig. 14b. The strength of inflow, however, was slightly changed; the inflow layer became thinner by 2346 JST.

4.3 The structure and evolution of the eyewall

The eyewall of T8514 is indicated by an arrow in Fig. 3. The following two features were observed. One is that the maximum-winds region was located near the maximum of radar reflectivity. The other is that curvature of the horizontal wind vectors was nearly the same as that of the radar reflectivity pattern.

According to data from the Mt. Fuji radar, the eyewall formed at 0010 JST on 31 August and reached its mature stage at 0046 JST, then decayed rapidly by 0119 JST. Thus its lifetime was about 70 minutes. The eyewall in the east of the storm center moved toward the typhoon center and disappeared.

The ground-relative movement of the eyewall was toward 345° at 10 ms^{-1} . Winds in the eyewall were

southerly to southeasterly and the wind speed was several meters per second on the typhoon-center side of the eyewall and more than 20 ms^{-1} in the eyewall. Thus, movement of the eyewall and wind field in the vicinity of the eyewall indicate that the eyewall cloud was moved by the airflow around it.

The wind and reflectivity fields around the eyewall are shown in Fig. 16. The southern half of these fields were observed at 0054 JST and the northern half of those were observed at 0103 JST. Two observational results were composed by correcting system movement between two observations.

A low-reflectivity area (under 15 dBZ) was found near the storm center. An echo-free area was also found near the storm center in Fig. 3. The eyewall of T8514 was observed as a core in excess of 42.5 dBZ northeast of the typhoon center. The width of the eyewall was about 20 km at the 0.8 km level. The size of core became smaller with height and above the 4.5 km level no cores with reflectivity exceeding 40 dBZ were found. This suggests that the eyewall was in its decaying stage as indicated by the Mt. Fuji radar data.

Winds blew nearly parallel to the eyewall at every level in Fig. 16. A maximum wind of 31 ms^{-1} was found outside the reflectivity core at the 0.8 km level. The feature that the maximum wind was present at a low level agrees with other observations (*e.g.*, Frank, 1977; Marks and Houze, 1987). The wind speed hardly changed in the eyewall and decreased abruptly on the inner side of the eyewall. The maximum wind was somewhat weaker at 1.5 km than at 0.8 km, but nearly the same wind field was observed. Upward transport of low-level momentum was small, because the eyewall was in its decaying stage at this time. Hence, the wind speed decreased even in the core of the eyewall above the 1.5 km level. The wind field was nearly the same from 2.5 km to 4.5 km height. Another feature of the wind field was local maximum winds located in the outer part (at larger distance from the storm center) of the eyewall at all levels. Jorgensen (1984b) found that the maximum wind of Hurricane Allen was located on the inner side of the reflectivity maximum below 1 km. The difference between our results and Jorgensen's will be discussed later.

The vertical structure of the eyewall is examined next. Figure 17a shows the distribution of reflectivity. A strong-reflectivity area exceeding 42.5 dBZ was found at 28–30 km from the storm center at the 0.8 km level. An area with reflectivity exceeding 35 dBZ became smaller with height. A low-reflectivity area below 15 dBZ was observed between the storm center and the 10 km range except at the 0.8 km level. The reflectivity maximum was slightly tilted inward with height.

The wind data shown in Figs. 17b–17c are winds relative to the eyewall. Figure 17b shows the ra-

dial component of the relative winds. Outside the 23 km range, a low-level inflow of 5 ms^{-1} was found below 1.5 km height. This relative inflow was the strongest inflow among the three systems (the outer rainband, the inner rainband, and the eyewall). Inflow was found at all layers between the 10 and 23 km ranges. By taking account of the the downdraft on the inner edge of the eyewall (Fig. 17d), a part of this inflow is derived from this downdraft. An outflow was observed between the 1.5 km and 3.5 km levels outside the 23 km range.

Figure 17c shows the tangential wind component of the relative wind. Positive values represent cyclonic flow. A maximum wind was found in the outer part (~ 30 km range) of the eyewall at the 0.8 km level. The radius of maximum winds (RMW) is indicated by a solid line. An anticyclonic component of relative flow was found on the inner side of the eyewall.

Figure 17d shows the vertical air velocity. The main updraft was located at ranges of 25 km and 32 km. Axes of the updraft were nearly vertical. Another updraft was found at a range of ~ 13 km where reflectivity was slightly stronger (Fig. 17a). A weak downdraft less than 0.5 ms^{-1} was found in a high-reflectivity region between 25 to 30 km from the typhoon center. A similar feature was found by Marks and Houze (1987). Another feature was that a downdraft of 1 ms^{-1} was present on the inner edge of the eyewall. The horizontal sections of vertical velocity (not shown) indicate that updrafts were predominant in the eyewall and convective-scale downdrafts were found on the inner edge of the eyewall.

The evolution of reflectivity and tangential (to circles about the storm center) wind fields of the eyewall are shown in Fig. 18. The high-reflectivity area exceeding 35 dBZ reached 6 km altitude at 0022 JST on 31 August (Fig. 18a). The reflectivity maximum sloped outward with height. This feature coincides with other observations (Jorgensen, 1984b; Marks and Houze, 1987) and results of numerical models (Yamasaki, 1983; Willoughby *et al.*, 1984a). Since the high-reflectivity region exceeding 35 dBZ was relatively high (~ 6 km) and the vertical gradient of reflectivity was weak, the eyewall was developing at this time. The tangential wind was relatively uniform in the high-reflectivity region of the eyewall (Fig. 18b). This indicates that the updraft in the eyewall was strong and that momentum at low levels was transported rapidly to upper layers. Shea and Gray (1973) found that vertical shear was weak in the inner-core region of a developing storm. Strong vertical shear of the tangential wind was observed only on the inner edge of the eyewall. The RMW and location of maximum reflectivity were almost coincident at this time.

Although reflectivity was higher at 0054 JST than at 0022 JST at low levels, the height of the high-

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Fig. 16. Horizontal sections of reflectivity and horizontal winds in the vicinity of the eyewall composite results at 0054 JST and 0104 JST on 31 August. Contours of reflectivity are drawn from 15 dBZ at intervals of 2.5 dB. Areas in excess of 35 dBZ are shaded. Symbols of tropical cyclones indicate the position of the typhoon center. The fan-shaped area indicates the position of the composite (averaged) vertical cross-section in Fig. 17.

Fig. 17. Vertical cross-section of the eyewall; (a) reflectivity, (b) radial component of relative winds, V_r' , (c) tangential component of relative winds, V_{θ}' , (d) vertical velocity. Contours of reflectivity are drawn from 10 dBZ at intervals of 2.5 dB. Areas exceeding 35 dBZ are shaded. Contours of V_r' and V_{θ}' are drawn at intervals of 1 ms^{-1} . Positive areas of V_r' and V_{θ}' are shaded. A positive value of V_r' indicates outflow from the storm-center side, and that of V_{θ}' the cyclonic component. Contours of vertical velocity are drawn every 0.5 ms^{-1} . Positive areas are shaded.

reflectivity area of the eyewall became lower at 0054 JST (Fig. 18c). This feature suggests that the eyewall cloud passed its mature stage. The RMW was located outside the maximum reflectivity at 0054 JST (Fig. 18d).

No cores with reflectivity exceeding 40 dBZ were found and the region exceeding 35 dBZ became smaller at 0110 JST about ten minutes before the eyewall disappeared (Fig. 18e). The RMW was completely outside the eyewall at this time (Fig. 18f). The eyewall moved toward the typhoon center and decayed.

Thus, in the developing stage of the eyewall, the tangential wind was almost uniform near the eyewall, and the RMW and the location of maximum reflectivity were almost coincident. The tangential wind field in the eyewall changed appreciably in the decaying stage and the RMW was located completely outside the eyewall.

The eyewall of T8514 decayed when it moved to the inner area (near the typhoon center) of the RMW. The horizontal sections of vertical velocity around the eyewall (not shown) indicated that a downdraft was predominant in the interior of the RMW. These observations suggest that since the

eyewall moved to the downdraft area, where vertical and horizontal shear of V_{θ} were large, it decayed.

5. Discussion

5.1 The maintenance mechanism of the outer rainband

The maintenance mechanism of the outer rainband is deduced from observational results as follows:

- (1) Warm air, which blew into the rainband from its inner side, and cold air, which was produced by cooling-by-melting and by cold downdraft in the outer part of the outer rainband, converged on the inner edge of the outer rainband and induced an updraft there.
- (2) Precipitation produced in this updraft was transported by southeasterly winds and formed the outer rainband.
- (3) Since the updraft around the center portion of the rainband was weak ($\sim 0.5 \text{ ms}^{-1}$) (Fig. 9d), a bright band was observed there. Precipitation particles which were present above the bright band were sustained by the weak updraft and made the elevated echo found in the RHI pattern in Fig. 10.
- (4) Shallow convective clouds in Fig. 10 were con-

Fig. 18. Evolution of the eyewall; (a), (c), (e) reflectivity, (b), (d), (f) tangential component of winds. Contours of reflectivity are drawn from 10 dBZ at intervals of 2.5 dB. Areas in excess of 35 dBZ are shaded. Contours of tangential wind are drawn at intervals of 1 ms^{-1} . Dot-dashed lines indicate the position of RMW.

sidered to have formed by convergence at low levels which was caused by the cold downdraft in the outer part of the rainband and warm inflow from the outside of the rainband. Since the inflow was weak, these clouds did not develop and did not play an important role in maintaining the rainband.

(5) Consequently, we suppose that the essential maintenance mechanism of the outer rainband is an interaction between warm southeasterly winds which blew from the inner side and cold air produced by cooling-by-melting and by the cold downdraft in the outer part of the rainband.

The structure of the outer rainband analysed here is compared with that of Ishihara *et al.* (1986). In their case the crossing angle of a rainband was also large (25°) and a low-level inflow converged on the inner edge of the rainband and produced an updraft. Thus, low-level inflow played an important role in maintaining the rainband. Contrary to their case,

the low-level inflow was very weak in the outer rainband of T8514 (Fig. 9b). Therefore, the low-level inflow did not play an important role in maintaining the outer rainband. Although features of the vertical velocity field of their rainband are similar to the outer rainband of T8514, the maintenance mechanism in their case was different from our case.

Yamasaki (1983) discussed the structure of a long-lasting rainband which was found in his numerical model. This rainband is organized when tangential winds are weak. He concluded that the essential mechanism to maintain the rainband is not only large-scale convergence of warm air from its outer side but also evaporative cooling and a cold downdraft. Different from Yamasaki's case, a downdraft was formed in the outer part of the rainband of T8514, and warm air which induced the updraft entered the rainband from its inner edge due to the large crossing angle of the rainband.

5.2 The maintenance mechanism of the inner rainband

The maintenance mechanism of the inner rainband inferred from its evolution and structure is as follows:

- (1) At first, core A which was considered to be an old cell existed in the inner part (nearer the typhoon center) of the inner rainband, and core B which was considered to be a younger cell existed in the outer part of the inner rainband (Fig. 13a). Band-relative inflow reached the inner edge of the outer core B, and induced an updraft there at 2329 JST (Fig. 13d). This updraft is considered to maintain core B.
- (2) The second important fact is that when the layer of low-level relative inflow became thinner, the updraft disappeared at low levels (Fig. 14d) and a prominent downdraft formed on the inner edge of the inner rainband. This suggests that the depth of the low level inflow layer (probably also the intensity of the low-level inflow) was closely related to the intensity of the updraft which maintained the inner rainband.
- (3) When new convective clouds formed at the outside (far side from the typhoon center) of the rainband, old clouds which were located in the interior of the rainband decayed because inflow could not reach it. This phenomenon may occur continually. Consequently, the inner rainband propagates outward. It is possible that the rainband decayed because the inflow from the outer side became weaker. Thus, the low-level inflow and the downdraft which was induced in the old cell on the storm center side are important to maintain the inner rainband.

The structure of the inner rainband was similar to the result of Tatehira (1961). Using surface data, he analysed the divergence field of a typhoon rainband and obtained the result that a convergence area was present in front (a large distance from the storm center) of the rainband and a divergence area was present at the rear of it. A similar divergence field was found at low levels of the inner rainband at 2346 JST (not shown). The crossing angle of the inner rainband of T8514 was nearly the same as that of Tatehira's rainband.

Barnes *et al.* (1983) analysed the structure of a rainband in Hurricane Floyd and found that low-level inflow decreases in the rainband and a mesoscale updraft forms in the same place. Barnes and Stossmeister (1986) revealed that the radial wind component associated with a decaying rainband changes from inflow to outflow. These results are also similar to that of T8514.

5.3 Comparison between the inner rainband and the outer rainband

In the outer rainband of T8514 the flow from the typhoon center side and the downdraft in the outer

part of the outer rainband played an essential role in its maintenance, while the low-level inflow and the downdraft on the inner edge of the rainband played an essential role in the maintenance of the inner band. We discuss the mechanism that made such a difference.

The crossing angle was much different for the outer rainband than for the inner rainband; the crossing angle of the outer rainband was $\sim 40^\circ$, while that of the inner rainband was $\sim 10^\circ$. The crossing angles were different because of the difference in magnitude of the horizontal shear of tangential winds. That is, the horizontal shear of the tangential winds in the inner rainband was larger than in the outer rainband (Figs. 9c and 13c). The tangential winds were large on the typhoon center side of the rainbands. Thus, it is inferred that the echoes in center side area moved faster than those in the area farther from the typhoon center. The difference of echo movement between the two areas was larger in the inner rainband than in the outer rainband. This made the crossing angle of the inner rainband small.

Moreover, the wind speed increases, resulting in strong frictional inflow in the boundary layer. Hence, inflow of 3 ms^{-1} was found in the inner rainband at 1 km height. On the other hand, band-relative radial inflow was almost negligible in the outer rainband at the same height.

In a three-dimensional numerical model of a tropical cyclone, Yamasaki (1986) found the relative locations of rainbands and cold areas which are produced by a cold downdraft. Although the cold area is located at almost the same position in rainbands in the outer domain, it is located on the inner edge of the rainband in the inner domain. He indicated that such a change is caused by different intensities of frictional inflow. Similar to this result, in the outer rainband a downdraft exists in its outer part, while in the inner rainband a downdraft exists on its inner edge in T8514.

From these observational facts of T8514 and the results of Yamasaki (1986), we deduced that the different maintenance mechanisms between the outer rainband and the inner rainband were due to the different magnitude of horizontal shear of the tangential winds and due to the different intensities of frictional inflow. That is, the flow which entered from the inner edge played an essential role in maintaining the outer rainband, which had a large crossing angle. On the other hand, the air which entered from the outer edge at lower levels was important to maintain the inner rainband, which had a small crossing angle.

5.4 Wind perturbation in the outer rainband

A wind field remarkably different from other levels was observed at the 4–5 km level in the outer rainband at 1938 JST (Fig. 6). It is possible that

perturbations of the wind field had some relationship to the “melting layer”.

Atlas *et al.* (1969) studied wind perturbations which were induced by cooling-by-melting. Applying the relation between cooling-by-melting snow and pressure perturbation to a gradient balance equation, they obtained the result that acceleration of tangential wind occurred on the low-pressure side (storm center side), and deceleration of tangential wind on the high-pressure side. Szeto *et al.* (1988a, b) studied the influence of cooling-by-melting on mesoscale circulations using a two-dimensional model, and obtained horizontal wind perturbation several meters per second in amplitude.

Similar to their studies, we found a temperature drop of $\sim 1^\circ\text{C}$ by cooling-by-melting below the 0°C level in the sounding of 2030 JST on 30 August 1985 at Tsukuba (Fig. 5). We also found that the tangential wind accelerated on the low pressure side (storm center side) of the “bright band” and decelerated on the high pressure side (side far from the storm center) near the 0°C level. The wind direction backed $\sim 40^\circ$ at the 4 km and 5 km levels. From these observations, we conclude that the wind perturbation around the outer rainband was induced by the cooling-by-melting of ice. Comparing wind fields below the 3 km level with that at the 4 and 5 km levels, we could deduce that the amplitude of perturbation was about 7 ms^{-1} . This amplitude of wind perturbation in our case was nearly two times that of Atlas’s case. Since the rainfall intensity observed during dual Doppler radar observation of the outer rainband of T8514 was nearly twice as high that in Atlas’s case, the amplitude of the perturbation was also nearly twice as high.

5.5 Comparison of the T8514 eyewall with hurricane eyewalls

There have been very few studies of the analysis of the fine structure of a tropical cyclones’ eyewall which could be compared with the present study. Jorgensen (1984b) analysed the structure of hurricane Allen and Marks and Houze (1987) hurricane Alicia, respectively. While the central pressures of Hurricanes Allen and Alicia were lower than that of T8514 (992 hPa) the maximum radar reflectivity of the eyewall of T8514 was almost the same as that of Hurricane Alicia. The region of high reflectivity of both T8514 and Hurricane Alicia extended vertically and the region of reflectivity maximum at each level was sloped outward with height in its mature stage.

RMWs sloped steeply outward with altitude in the eyewalls of Hurricane Allen and Alicia; however, that of T8514 was almost vertical. The position of the RMW was 3–5 km inward of the reflectivity maximum in Hurricane Allen and was just on the outer

edge of area of the reflectivity maximum in Hurricane Alicia, and was ~ 5 km out of the area of reflectivity maximum T8514 at 0054 JST on 31 August. Thus, the difference in structures of the eyewalls between the two hurricanes and T8514 was due to the different intensities of low-level inflow.

In general, inflow air had a large angular momentum, tangential wind increases when it approaches the typhoon center. The inflow air rises at the RMW and flows out at upper levels. Precipitation particles are produced in the updraft and they are transported outward in the outflow at upper levels. In the case of a strong radial inflow at lower levels, the RMW is located just on the inner edge of the eyewall and the RMW slopes outward with height (Yamasaki, 1983). Contrary to this, the RMW in T8514 in the decaying stage was located outside the eyewall, because of weak inflow at lower levels.

Radial inflow was evident below 1.5 km in the northwestern part of the storm center in Hurricane Allen (Jorgensen, 1984b). Its maximum inflow was 25 ms^{-1} . A prominent outflow of $15\text{--}25\text{ ms}^{-1}$ was found above 2.5 km inward of the RMW in Hurricane Allen. A weak radial relative inflow of $\sim 5\text{ ms}^{-1}$ was found below 0.8 km in T8514. The radial inflow of T8514 was weak because its central pressure was high.

The above discussion indicates that, while the reflectivity structure of the eyewall is not much different between a strong tropical cyclone and a weak one, the strength of radial inflow, distribution of tangential wind, and the slope of the RMW are much different.

6. Conclusions

By use of two Doppler radars, we observed the main components of Typhoon 8514: the outer rainband, the inner rainband, and the eyewall. A schematic cross section of T8514 is shown in Fig. 19.

The outer rainband was located about 150 km north of the typhoon center. Convective clouds existed in the inner portion of the outer rainband. The “bright band” was observed in the outer rainband. A two-layer structure, of shallow convective clouds and an elevated stratiform cloud, was present in the outer part of the outer rainband. A perturbed wind field formed around the bright band owing to cold air which was produced by cooling-by-melting. Air flow from the inner side of the rainband played an essential role in the maintenance of the outer rainband (In horizontal section, air of the outer area of the typhoon flows from the inner side of the outer rainband).

The inner rainband of T8514 was located about 60 km from the storm center. The “bright band” was not present in this rainband. Since the reflectivity maximum was nearly vertical, this rainband

Fig. 19. Schematic illustration of the structure of T8514.

was considered to be a convective one. Considering the evolution of the wind field of the rainband, low-level inflow is essential to maintain this rainband.

The eyewall was present at about 30 km from the storm center. Although the analysed eyewall was in its decaying stage, its maximum reflectivity of 42.5 dBZ was strongest among the three parts of the typhoon. The reflectivity abruptly decreased with height. Inflow to the storm center was found only at the 0.8 km level. A maximum outflow was present at the 1.5 km level. Maximum tangential wind of 31 ms^{-1} also was present at the 0.8 km level.

The structure of T8514 is different from that of strong hurricanes and that of a simulated typhoon in the slant angle of the reflectivity maximum and location of the RMW. It is an open question as to whether these features of the structure of Typhoon 8514 are due to its weak intensity or due to the changing characteristics of typhoons in middle latitudes.

Acknowledgements

The authors wish to express their hearty thanks to Dr. Aoyagi for his cooperation in data acquisition. They also thank Dr. T. Maruyama and three anonymous reviewers for their helpful comments. They also thank the personnel of the Edogawa Office of the Ministry of Construction for providing the Doppler radar site. They thank the personnel of the Tokyo District Meteorological Observatory and the Aerological Observatory for providing the observational data. The analysis of Doppler radar data were made using the HITAC-M280D of MRI.

References

- Atlas, D., R. Tatehira, R.C. Srivastava, W. Matker and R.E. Carbone, 1969: Precipitation-induced mesoscale wind perturbations in the melting layer. *Quart. J. Roy. Meteor. Soc.*, **95**, 544–560.
- Barnes, G.M., E.J. Zipser, D. Jorgensen and F. Marks, Jr., 1983: Mesoscale and convective structure of a hurricane rainband. *J. Atmos. Sci.*, **40**, 2125–2137.
- Barnes, G.M. and G.J. Stossmeister, 1986: The structure and decay of a rainband in Hurricane Irene (1981). *Mon. Wea. Rev.*, **114**, 2590–2601.
- Barnes, G.M., J.F. Gamarch, M.A. LeMone and G.J. Stossmeister, 1991: A convective cell in hurricane rainband. *Mon. Wea. Rev.*, **119**, 776–794.
- Bluestein, H.B. and D.S. Hazen, 1989: Doppler-radar analysis of a tropical cyclone over land: Hurricane Alicia (1983) in Oklahoma. *Mon. Wea. Rev.*, **117**, 2594–2611.
- Doviak, R.J., P.S. Ray, R.G. Strauch and L.J. Miller, 1976: Error estimation in wind fields derived from dual-Doppler radar measurement. *J. Appl. Meteor.*, **15**, 868–878.
- Foot, G.B. and P.S. du Toit, 1969: Terminal velocity of raindrops aloft. *J. Appl. Meteor.*, **8**, 249–253.
- Frank, W.M., 1977: The structure and energetics of the tropical cyclone. I. Storm structure. *Mon. Wea. Rev.*, **105**, 1119–1135.
- Frank, W.M., 1984: A composite analysis of the core of a mature hurricane. *Mon. Wea. Rev.*, **112**, 2401–2420.
- Gal-Chen, T., 1982: Errors in fixed and moving frame of references: Applications for conventional and Doppler radar analysis. *J. Atmos. Sci.*, **39**, 2279–2300.
- Gentry, R.C., 1964: *A study of hurricane rainbands*. NHRP Rep. No. 69, 85 pp.
- Gunn, K.L.S. and T.W.R. East, 1954: The microwave properties of precipitation particles. *Quart. J. Roy. Meteor. Soc.*, **80**, 522–545.
- Ishihara, M., Z. Yanagisawa, H. Sakakibara, K. Matsuura and J. Aoyagi, 1986: Structure of a typhoon rainband observed by two Doppler radars. *J. Meteor. Soc. Japan*, **64**, 923–939.
- Jorgensen, D.P., 1984a: Mesoscale and convective-scale characteristics of mature hurricanes. Part I: General observations by research aircraft. *J. Atmos. Sci.*, **41**, 1268–1285.
- Jorgensen, D.P., 1984b: Mesoscale and convective-scale characteristics of mature hurricanes. Part II: Inner core structure of hurricane Allen (1980). *J. Atmos. Sci.*, **41**, 1287–1311.
- Jorgensen, D.P. and F.D. Marks, Jr., 1984: Airborne Doppler radar study of the structure and three-dimensional airflow within a hurricane rainband. *Preprints, 22nd Conf. on Radar Meteorology, A.M.S., Boston, Mass.*, 572–577.
- Jou, B.J.D., 1991: Mesoscale structure of typhoon Yancy. *Preprints, 25th Conf. on Radar Meteorology, A.M.S., Boston, Mass.*, 694–697.
- Lee, C.W. and Y.C. Tsai, 1991: An analyses of “YANCY” Typhoon’s (1990) structure by using sin-

- gle Doppler radar observation. *Preprints, 25th Conf. on Radar Meteorology, A.M.S., Boston, Mass.*, 698–701.
- Lhermitte, R.M. and L.J. Miller, 1970: Doppler radar methodology for the observation of convective storms. *Preprints, 14th Conf. on Radar Meteorology, A.M.S., Boston, Mass.*, 133–138.
- Matsumoto, S. and H. Okamura, 1985: The internal gravity wave observed in the Typhoon T8124 (Gay). *J. Meteor. Soc. Japan*, **63**, 37–51.
- Marks, F.D., Jr. and R.A. Houze, Jr., 1984: Airborne Doppler radar observations in hurricane Debby. *Bull. Amer. Meteor. Soc.*, **65**, 569–582.
- Marks, F.D., Jr. and R.A. Houze, Jr., 1987: Inner core structure of hurricane Alicia from airborne Doppler radar observations. *J. Atmos. Sci.*, **44**, 1296–1317.
- Muramatsu, T., 1982: Extratropical transformation of mature typhoon: The case study of typhoon 7916, Owen. *Tenki*, **29**, 1199–1212 (in Japanese).
- Powell, M.D., 1990: Boundary layer structure and dynamics in outer hurricane rainbands. Part I: Mesoscale rainfall and kinematic structure. *Mon. Wea. Rev.*, **118**, 891–917.
- Rogers, R.R., 1964: An extension of the Z-R relation for Doppler radar. *Preprints, 11th Conf. on Radar Meteorology, A.M.S., Boston, Mass.*, 158–161.
- Sakakibara, H., M. Ishihara and Z. Yanagisawa, 1985: Structure of a typhoon rainstorm in the middle latitudes observed by Doppler radar. *J. Meteor. Soc. Japan*, **63**, 901–922.
- Shea, D.J. and W.M. Gray, 1973: The hurricane's inner core region. I. Symmetric and asymmetric structure. *J. Atmos. Sci.*, **30**, 1544–1563.
- Szeto, K.A., C.A. Lin and R.E. Stewart, 1988a: Mesoscale circulations forced by melting snow. Part I: Basic simulations and dynamics. *J. Atmos. Sci.*, **45**, 1629–1641.
- Szeto, K.A., R.E. Stewart and C.A. Lin, 1988b: Mesoscale circulations forced by melting snow. Part II: Application to meteorological features. *J. Atmos. Sci.*, **45**, 1642–1650.
- Tatehira, R., 1961: A mesosynoptic and radar analysis of typhoon rain band, case study of typhoon "Helen", 1958. *Proc. Second Tech. Conf. Hurricanes, Amer. Meteor. Sci.*, 115–126.
- Wexler, H., 1947: Structure of hurricanes as determined by radar. *Ann. N. Y. Acad. Sci.*, **48**, 821–844.
- Willoughby, H.E., H.-L. Jin, S.J. Lord and J.M. Piotrowicz, 1984a: Hurricane structure and evolution simulated by axisymmetric, nonhydrostatic numerical model. *J. Atmos. Sci.*, **41**, 1169–1186.
- Willoughby, H.E., F.D. Marks, Jr. and R.J. Feinberg, 1984b: Stationary and moving convective bands in hurricanes. *J. Atmos. Sci.*, **41**, 3189–3211.
- Yamasaki, M., 1983: A further study of the tropical cyclone without parameterizing the effects of cumulus convection. *Papers Meteor. Geophys.*, **34**, 221–260.
- Yamasaki, M., 1986: A three-dimensional tropical cyclone model with parameterized cumulus convection. *Papers Meteor. Geophys.*, **37**, 205–234.

デュアルドップラーレーダーによって観測された台風 8514 号の全体構造 —外側降雨帯から眼の壁雲まで—

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1985 年 8 月 30 日に日本中央に上陸した、台風 8514 号の降雨帯と眼の壁雲を地上の 2 台のドップラーレーダーを用いて観測した。この論文の主な目的は、デュアルドップラーレーダーのデータを用いて、台風 8514 号の全体構造を記述することである。

台風 8514 号は小型で弱い台風であったが、熱帯低気圧の性質をよく維持していた。すなわち、らせん状の降雨帯をとめない（外側降雨帯と内側降雨帯）、上部に暖気核を持っていた。

外側降雨帯は、台風中心から約 150 km に位置した、らせん状の降雨帯である。この降雨帯は、連続した層状雲と、散在した対流雲からできていた。「ブライトバンド」が、この降雨帯内で観測された。融解による冷却によってつくられた風の乱れが、ブライトバンドのすぐ下で観測された。1.5 ms⁻¹の上昇流が外側降雨帯の内縁に主に南東風の収束によってつくられた。この上昇流が外側降雨帯を維持していた。

内側降雨帯は台風中心から約 60 km に位置した対流性のらせん状降雨帯である。反射強度と鉛直流の分布を調べると、古いセルが降雨帯の内側部分に、一方新しいエコーセルが外側部分にあることが分かった。台風中心に流入する空気が、内側降雨帯の下層で観測された。この流入する空気は、新しいエコーセルの内縁で上昇流をつくっていた。この流入する空気の層の厚さが薄くなったとき、内側降雨帯は衰弱した。

この事は、下層での空気の流入が内側降雨帯の維持に重要である事を示している。

台風 8514 号では、下層での眼の壁雲への流入が弱かったため、最大風速半径 (RMW) は、眼の壁雲の反射強度最大の軸の外側に存在した。眼の壁雲は、RMW より台風中心に近い側に移動したときに衰弱した。これは RMW の内側では、下降流が卓越するためと考えられる。