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WIND FIELDS OF TYPHOON SONGDA (2004) OBSERVED BY THE OKINAWA DOPPLER RADAR (COBRA)

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1. INTRODUCTION

Typhoon Songda (T0418 in a Japanese reference) passed over Okinawa island on September 5, 2004, and the typhoon center passed over the C-band Okinawa Bistatic Polarimetric Radar (COBRA) developed by the National Institute of Information and Communications Technology (Nakagawa et al, 2003). The COBRA observed the typhoon in its mature stage before and after the passage for 18 hours. Although the typhoon brought a historical record of the minimum pressure in Okinawa island, the damage was not so serious in Okinawa. However, it caused extensive damage to several places in the main island of Japan in next two days.

Many studies on tropical cyclone structure using Doppler radar have been reported. Airborne Doppler radar observations (e.g. Jorgensen and Marks, 1984; Marks et al, 1992; Roux and Viltard, 1995) are effective to investigate the structure in suitable areas of an off-shore tropical cyclone by long-range flight observation. On the other hand, ground-based Doppler radar observations (e.g. Ishihara et al, 1986; Tabata et al, 1992) have the advantages of three-dimensional measurement continuously at a short-period interval. However, the non-mobile ground-based radar has a few chance to observe interesting parts of tropical cyclones because of the limited observation range. For a general Doppler radar, long-range observation with low PRF is incompatible with large-velocity observation, which requires high PRF(s). Since the COBRA has a function of arbitrary setting of the radar parameters, we can realize the most suitable observation in both a long-range and a large-velocity using an optimum staggered PRFs setting (e.g. 500 Hz and 375 Hz PRFs realize 290 km range and +/-21 m/s velocity measurement for a lower elevation scan). In addition to Doppler velocity data, the COBRA measures full polatimetric data (ZHH, ZVV, ZHV, ZDR, LDR, rhoHV, phiDP, etc) at the same time.

In this study, as a first step analysis of the precious data of typhoon Songda observed by COBRA, the mean tangential velocities of the typhoon are calculated from the single Doppler data using PPI scans with a lower elevation angle (0.9 degrees) only. And the tangential velocities are evaluated by comparisons with ground-level wind speed observed by an automatic weather station (AWS) and theoretical gradient wind.

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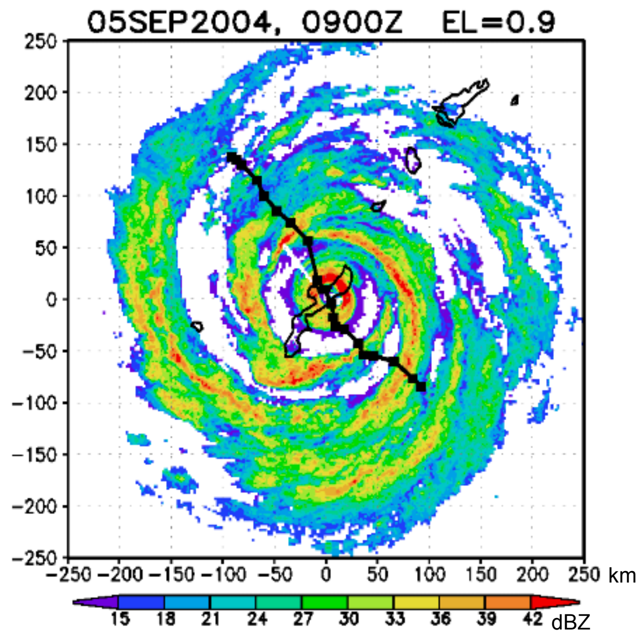

Fig. 1 Horizontal distribution of radar reflectivity when the typhoon center located over the COBRA radar site. Thick line with circle marks indicate the trajectory and the positions every one hour of the typhoon center.

2. COBRA OBSERVATION

The COBRA observation sequence every 10 minutes includes a volume scans by 14 PPI scans (from 0.5 to 20 degrees in elevation angles) and four RHI scans (in four azimuth angles). The recorded observation range is 280 km with the range resolution of 300 m for the lower elevation angle PPI scans. Both the beam width and azimuth resolution are about 0.9 degrees. Transmitting polarization is +45 degrees linear, and H and V independent digital receivers are used. The COBRA data used in this analysis is from 0000Z to 1930Z on September 05, 2004, though a missing observation period caused by transmitter

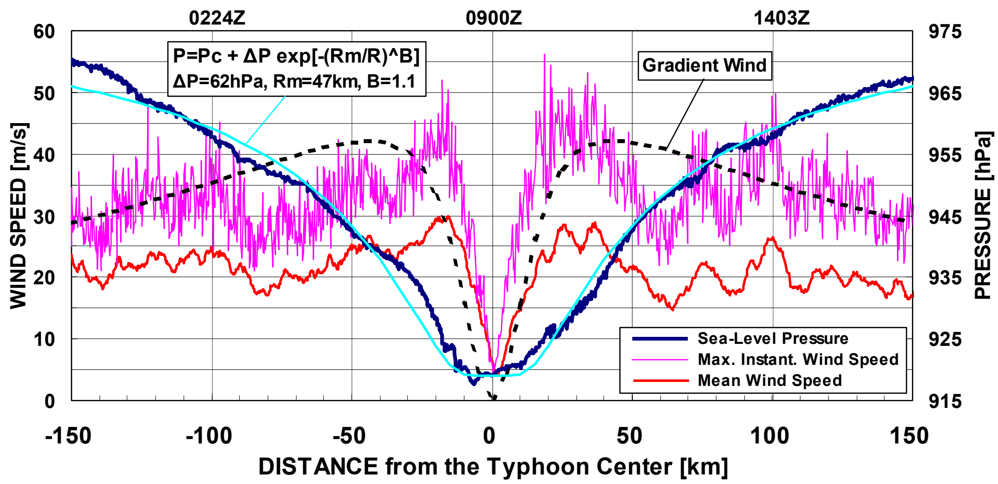

Fig. 2 Time changes of sea-level pressure, maximum wind speed, and mean wind speed observed at the COBRA radar site. Horizontal axis is translated into the distance from the typhoon center. Thin line shows the regression curve of the pressure change, and dot line shows the gradient wind speed calculated from the pressure regression expression.

trouble between 1050Z and 1220Z is included. Before 1050Z, the COBRA was operated by the pulse compression mode (COBRA+) using dual-TWTA transmitters (Nakagawa et al, 2005), while dual-klystron transmitters were used after 1220Z. Although the observation parameter and data type of COBRA+ are almost the same as COBRA, the sensitivity of COBRA+ is better than COBRA. Figure 1 shows the horizontal distribution of radar reflectivity at 0900Z, when the typhoon center located over the COBRA site. Since the circular eyewall echo was very clear during the observation period, it is easy to determine the position of the typhoon center. The traveling speed of the typhoon center was 3 to 4 m/s before landfall in Okinawa, and was 5 to 6 m/s after passing Okinawa island. The traveling speed around the center may represent the motion of the typhoon system because the typhoon maintained the axial symmetry structure as shown in Fig. 1 during the observation period.

3. SURFACE WIND SPEED AND GRADIENT WIND

The surface wind speed and pressure data observed by AWS installed at the COBRA site are investigated. The AWS records the basic meteorological data (pressure, sea-level pressure, temperature, humidity, mean/instantaneous/maximum wind speeds and directions, solar radiation, rainfall rate) every one minute. In Fig 2, the every one minute data of sea-level pressure, maximum instantaneous wind speed, and mean wind speed are plotted. The horizontal axis is translated into the distance from the typhoon center from the time axis using the typhoon traveling speed mentioned the above. The time before (after) the typhoon center passed over the COBRA site is expressed as the negative (positive) distance. The minimum sea-level pressure dip of 917.6 hPa was recorded at 0835Z. However, the minimum wind speed was recorded at between 0900Z and 0906Z, which was the time of passing the typhoon center over the COBRA site. The passing time is confirmed by a series of eyewall echo images observed by COBRA. The maximum instantaneous wind speed of 56.1 m/s was recorded at 0957Z (19 km in distance in Fig. 2), and the maximum mean wind speed reached about 30 m/s before and after the typhoon center passage. The distribution of pressure and wind speed in Fig. 2 also indicates the typhoon has a symmetric structure.

A regression curve of the observed pressure change is calculated using an equation introduced by Holland (1980). The regression curve using four parameters (Pc, ΔP, Rm, B shown in Fig. 2) looks to be good agreement with the original data. However, the parameter of Rm (=47 km), which indicates the radius of the maximum cyclostrophic wind speed, may be too large comparing with the actual radius of about 20 km. As a well-known theory, the tangential velocity of a typhoon is approximated by the gradient wind, which balances with both the pressure gradient force and the centrifugal and Coriolis force. Hence, using the regression curve as the pressure gradient, the gradient wind is calculated. The result shown in Fig. 2 indicates that the maximum wind speed is 42 m/s at the distance of Rm, and the wind speed decreases with distance to 30 m/s at the distance of 150 km. The distribution of the gradient wind is comparable to the distribution of the maximum instantaneous wind speed except the radius of the maximum wind speed.

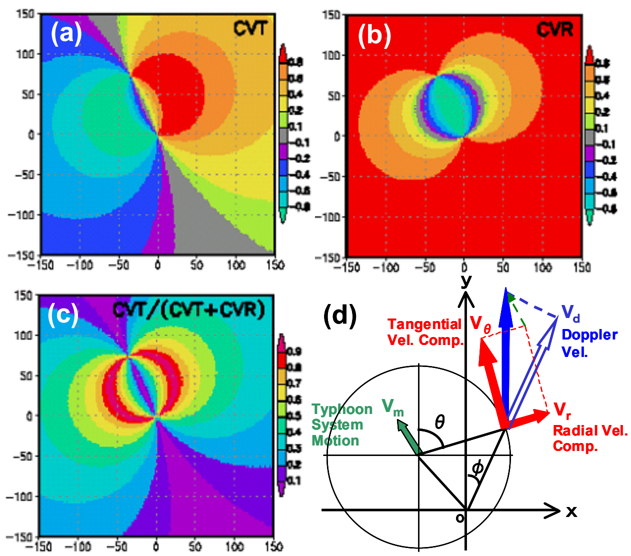

Fig. 3 Explanation of the velocity components included in observed Doppler velocity. Horizontal distribution of coefficients of (a) tangential velocity, (b) radial velocity, and (c) contribution rate of tangential velocity. (d) schematic display of the velocity components.

4. TANGENTIAL WIND FROM DOPPLER VELOCITY

Doppler velocity data observe by the COBRA includes three wind components as shown in Fig. 3 (d), that are the components of tangential velocity (V_θ) and radial velocity (V_r) relative to the typhoon center, and

$$V_d = V_\theta \sin(\theta - \phi) + V_r \cos(\theta - \phi) + V_m \cos(\phi - \mu)$$

the typhoon system motion (V_m). The observed Doppler velocity (V_d) is expressed by where θ is the azimuth angle from the typhoon center to a measurement point, ϕ is the azimuth from the radar to the point, and μ is the azimuth direction of the typhoon system motion. In a case of the typhoon center located at (-35km, 75km), the horizontal distributions of the coefficients of the first and second terms in the equation are shown in Fig. 3 (a) and (b) respectively. The contribution rate of the tangential velocity component (first term coefficient) is shown in Fig. 3 (c). The distribution of the contribution rate indicates that the large contribution area extends to two arc-shape areas on the both sides of a line between the radar and the typhoon center. In these areas, it means that the tangential wind component dominates in observed Doppler velocity. Considering the tangential velocity has several times the radial velocity for general typhoons, the tangential velocity is calculated within the area of the contribution rate more than 0.3 (30%). Although the typhoon traveling velocity component (third term in the equation) is subtracted from Doppler velocity first, the unknown radial velocity is ignored. As other information of the Fig. 3 (c), it is necessary that the typhoon center should be apart from the radar to obtain the tangential velocity over long-distance regions.

Figure 4 shows the results of the estimated tangential velocities at 0230Z, 0430Z, and 1230Z. Since it is hard to distinguish between valid data and large-error data geometrically in the horizontal distribution of estimated tangential velocity, the mean tangential velocities, which are averaged around the typhoon center on each distance, are shown in Fig. 4. At any time of the analyses, the mean tangential velocity has a maximum peak value of about 40 m/s at between 15 km and 20 km in distance, while almost flat distribution of about 30 m/s appears beyond 50 km in distance. The values of the mean tangential velocity correspond to the gradient wind shown in Fig.2. Although the distribution of the estimated tangential velocity is similar to the maximum instantaneous wind speed at surface, the properties of the two kinds of wind speeds are different. While the Doppler radar measures velocity in a special and temporal averaging area at altitudes of between 2 and 4 km, the instantaneous wind speed includes turbulent flow and gust at surface.

The peak wind speed appears in a distance of about 20 km from the typhoon center. This fact is confirmed by both the Doppler estimation and the AWS observation. Figure 5 shows the expanded horizontal distribution of radar reflectivity at 0910Z. The radius of the strongest circular echo, which may indicate the internal surface of the eyewall cloud, is 18 km. This radius is coincide with the location of the wind peaks in both estimated mean tangential velocity and the surface instantaneous wind observed by AWS. Also, two wind peaks at 25 km and 35 km in the surface mean wind speed shown in Fig. 2 seems to correspond with the double structure of eyewall echo appeared in the southern part in Fig. 5. Although some spiral outer rain-bands appeared in between 50 km and 100 km in distance in Fig. 5 must affect the wind fields, the evaluation in detail will be a future work.

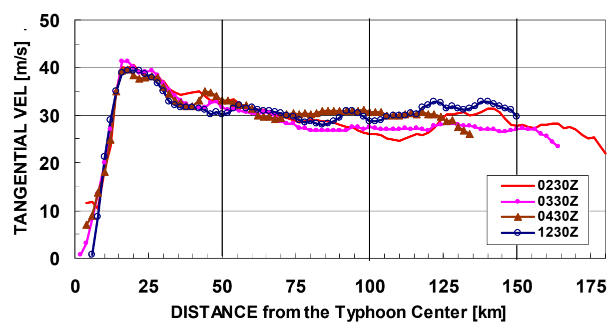

Fig. 4 Estimated mean tangential velocities at 0230Z, 0430Z, and 1230Z as a function of the distance from the typhoon center.

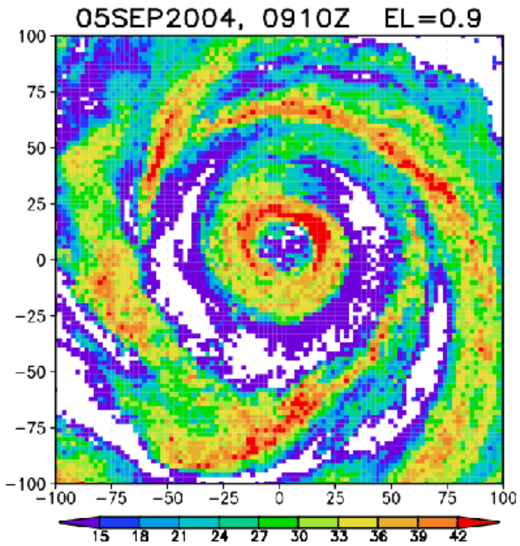

Fig. 5 Expanded horizontal distribution of radar reflectivity around the typhoon center at 0910Z.

5. CONCLUDING REMARKS

A single Doppler radar (COBRA) observed typhoon Songda, which passed over the radar site in Okinawa, on September 5, 2004. The COBRA measure the structure and velocity fields of the mature stage typhoon within the range of 280 km for 18 hours. The typhoon has an axial symmetry structure and a clear eyewall with a radius of 20 km. First, surface wind speed and pressure change observed by AWS are investigated. The mean wind speed of 30 m/s and the maximum instantaneous wind speed of 56 m/s were observed at 20 km from the typhoon center. A gradient wind, which is calculated from the horizontal pressure gradient estimated from a regression curve of the measured pressure change and the typhoon motion, shows that the theoretical maximum wind speed is 42 m/s. Second, the distribution of tangential wind speed of the typhoon is retrieved from the single Doppler radar data. The estimated mean tangential wind speed has a maximum of 40 m/s at 20 km from the typhoon center. Since the radius of the eyewall echo is 20 km, it means that the maximum wind speed occurs in the eyewall. The coincident of the maximum tangential wind and the eyewall was reported by Willoughby (1990) from many hurricane observations. The radial distribution of the mean tangential wind speed that is estimated from radar observations at different times, which represents the wind speed between 2 km and 4 km in height, is consistent with the gradient wind distribution.

Since the typhoon maintained its axial symmetric structure during the radar observation period, the entire wind fields of the typhoon are investigated as a first step of the data analyses. However, the COBRA observation data includes fine structure information on not only Doppler velocity but also full polarimetric data in a three-dimensional volume every 10 minutes. Actually, double eyewall structure and proportional some spiral outer rain-bands were observed. The interesting features and three-dimensional kinematic structure will be revealed in the next studies.

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