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STRUCTURAL TRANSITION OF TYPHOON 0416 OBSERVED BY WEATHER RADARS, RADIOSONDES AND WIND PROFILERS

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1 Introduction

Most tropical cyclones (TCs) developed in low latitudes gradually became weak and some of them transformed into extratropical cyclone at mid-latitude. The transformation from TC to extratropical cyclone is called extratropical transformation. As a lot of researchers have had greater concern about the topic of extratropical transformations, many studies have been conducted for years. For example, Muramatsu (1982) discovered that the thermal structure of TC in lower altitude became asymmetrical and precipitating cloud of that shifted poleward in the region of westerlies, using weather satellite, radio sonde and weather radar. He also suggested that characteristics of TC were lost by the intrusion of dry air into the vortex center. Shimazu (1998) analyzed the precipitating clouds of TC at mid-latitudes and named the inverted triangle–shaped precipitating clouds which formed in the northern side of TC "Delta rain shield", using weather radar. Kitabatake (2002) suggested that the strong horizontal divergence of upper troposphere was gradually lost in the process of extratropical transformation and that the TC lost the diabatically–generated potential vorticity anomaly when it was supposed to complete the extratropical transformation, using the gridded global analysis (GANAL) produced by Japan Meteorological Agency (JMA). Yamashita and Ishihara (2005) showed that the rotation axis of TC which stands upright gradually inclined and the connection between rotation axis and trough became strong as TC moved to mid-latitude, using wind profiler network and data acquisition system (WINDAS) operated by JMA. These studies have made considerable contributions to understanding the process of extratropical transformation. However, there is no clear criterion about the difference between TC and extratropical cyclone.

The TC (Typhoon 0416) which was developed in the sea near Marshall Islands (13.2°N, 160.4°E) on 19 August, 2004 moved northward and passed over the Japanese Archipelago during 29–31. In this study, we examined transition process of the wind behavior (using WINDAS data; Naze, Kumamoto, Tottori, Muroran) and thermal structure (using radio sonde data; Naze, Kagoshima, Wajima, Sapporo) of TC based on structural change of precipitating clouds obtained by weather radar observations. When we analyze, transitional process of the TC was classified into four stages (see Sec. 3). Trajectory of TC and observation sites are shown in Fig.1.

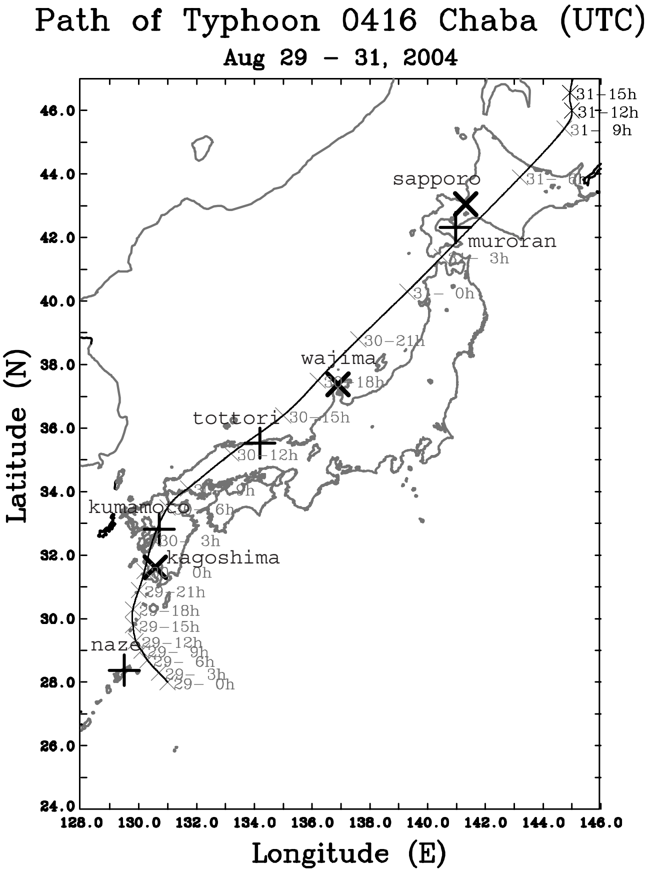

Fig.1: The trajectory of TC (solid line), observation sites of WINDAS (+) and observation sites of radio sonde(×). Symbols × on the trajectory signify the TC center every three hours of the best track data reported by JMA.

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2 Observation instruments and analysis method

In order to examine detailed wind behavior and its variations in the vicinity of TC center which was not discussed in any previous study, we used observation data of WINDAS (Kato *et al.*, 2003). WINDAS is composed of 26 wind profilers from 2001 (31 profilers from 2003) and constituting radar of each site is L-band (operational frequency 1357.5 MHz) wind profiler (Lower Troposphere Radar;LTR) developed in our laboratory. Time and height resolutions of LTR are 1 minute and 300 m, respectively and LTR can observe continuously in any weather conditions up to middle troposphere (Hashiguchi *et al.*,2004). To examine the wind behavior relative to TC center, moving speed of TC is subtracted from the observed wind and then divided into radial and tangential components. Here, we assume that TC has cylindrical structures and TC center and moving speed of TC do not change with height.

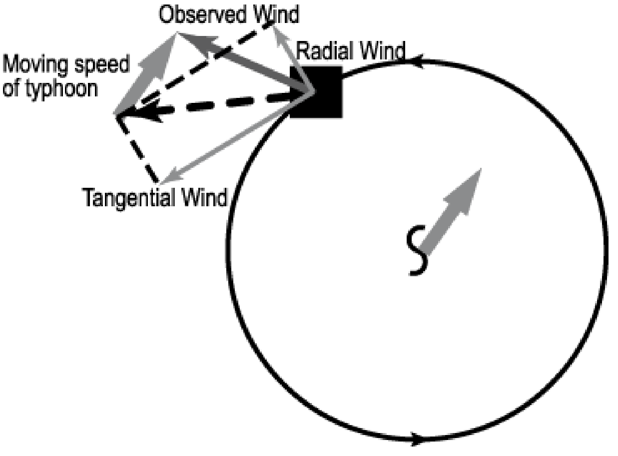
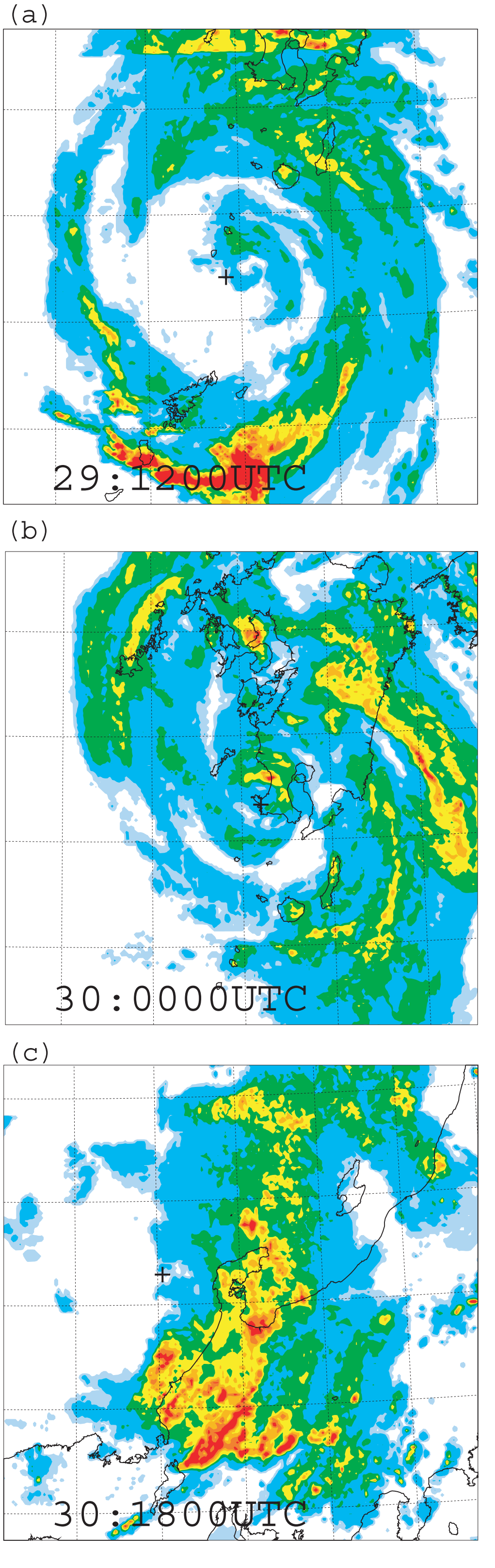


Fig.2: Analysis method of horizontal wind observed by WINDAS (Teshiba *et al.*, 2001)

3 Precipitating clouds obtained by weather radar

Precipitating distributions in the vicinity of TC center were rapidly changed in baroclinic zone near Japan. In this process, however, delta rain shield which pointed out by Shimazu (1998) was not seen. In this study, based on structural change of precipitating clouds obtained by weather radars operated by JMA, transition process of the TC was classified into four stages as follows. Stage 1: From 00 UTC 29 August to 23 UTC 29, TC eye, surrounding eyewall and spiral rain bands (Willoughby *et al.*,1984) are seen (see Fig.3a). Stage 2: From 00 UTC 30 to 08 UTC 30, TC eye is not seen, however, spiral rain bands in front side of TC is still seen obviously (see Fig.3b). Stage 3: From 09 UTC 30 to 00 UTC 31, though strong precipitating cloud (more than 50 mm/h rainfall) in front side (especially in the southeast quadrant of TC) is seen, spiral rain band become vague and precipitating cloud in the rear side become narrower (see Fig.3c). Stage 4: From 01 UTC to 06 UTC 31, strong precipitating cloud becomes rather weak (see Fig.3d). As the TC transformed into extratropical cyclone in the Sea of Okhotsk where no WINDAS and radio sonde observation conduct, we discuss the structural change of TC by just before the extratropical transition.



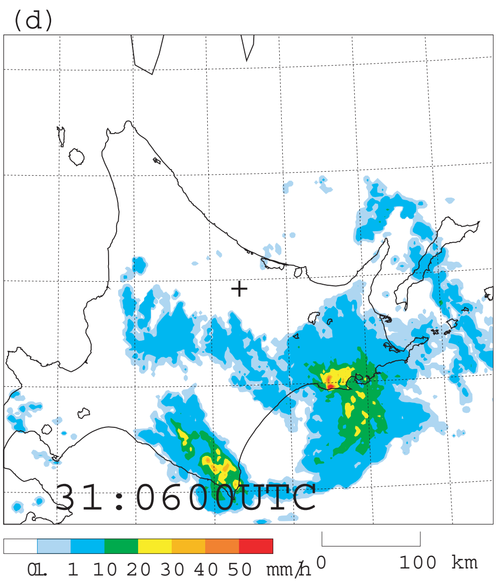


Fig.3: Horizontal rainfall intensity distributions observed by weather radar at (a)12 UTC 29, (b)01 UTC 30, (c)18 UTC 30, (d)06 UTC 31. Symbols + signify the TC center at each time.

4 Thermal structures observed by radio sonde

As the TC approached, radio sonde observation were carried out every 6 hours in Kagoshima (STAGE 2), Wajima (STAGE 3) and Sapporo (STAGE4). Temporal variations of equivalent potential temperature calculated by radio sonde observation data in Wajima (a) and Sapporo (b) are shown in Fig.4. In this figure, horizontal temporal axis goes from right side to left side. In Wajima, high equivalent potential temperature more than 366 K can be seen at 18 UTC 30 in 6–8 km altitude and the horizontal gradient of equivalent potential temperature is stronger than vertical gradient, worm core which is the characteristics of TC can be seen obviously (see Fig4a). In Sapporo, relative weak worm core (more than 357 K) in comparison with that of in Wajima can be seen in 6–8 km altitude. Though precipitating cloud do not have own characteristics of TC at this time (see Fig.3d), thermal structure still has worm core structures while it is relative weak.

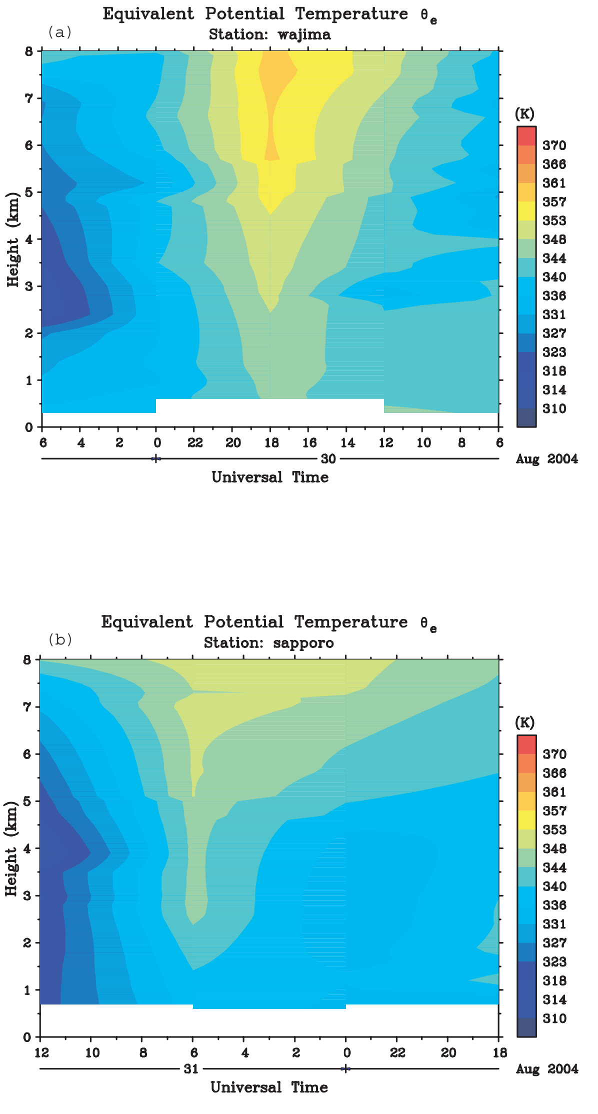


Fig.4:Temporal variations of equivalent potential temperature in (a) Wajima and (b) Sapporo. The closest time of approach are 18 UTC 30 and 06 UTC 31, respectively.

Vertical profiles of relative humidity at 12 UTC 30 (in front side of TC), 18 UTC 30 (in the vicinity of TC center) and 06 UTC 31 (in rear side of TC) in Wajima is shown in Fig.5. Observation at 12 UTC 30, dry and wet layer are seen below 5 km altitude and in 5–7.5 km altitude, respectively. Vertical gradient of relative humidity in 1–2.5 km and in 3.5–5 km altitude are very large. At 18 UTC 30, almost all layers (especially in 4–6 km altitude) are close to saturation. At 06 UTC 31, relative dry (relative humidity less than 20 %) and wet (relative humidity more than 70 %) layer are seen above 2.5 km and below 2 km altitude, respectively. Vertical gradient of relative humidity in 2–2.3 km altitude is very large. As we mentioned above, dry (wet) layer is seen in lower (higher) altitude in the front side of TC and in higher (lower) altitude in the rear side of TC. Vertical profiles of potential temperature, equivalent potential temperature and saturated equivalent temperature at 06 UTC 31 in Wajima is shown in Fig.6. Stable and unstable layers exist above 2.5 km and below 2.5 km altitude, respectively. Though dry air intrudes from upper layer into middle troposphere, re-intensification of TC did not happen since the stable layer exists in middle troposphere.

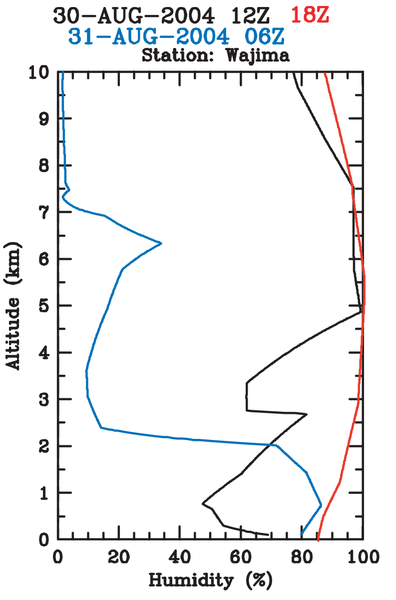


Fig.5: Vertical profiles of relative humidity at 12 UTC 30(black line), 18 UTC 30 (red line) and 06 UTC 31 (blue line) in Wajima.

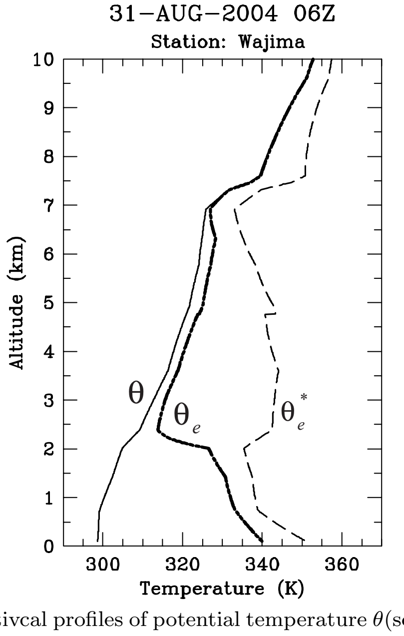


Fig.6: Vertivcal profiles of potential temperature θ(solid line), equivalent potential temperature θ_e(bold line), saturated potential temperature θ_e^*(dashed line) at 06 UTC 31 in Wajima.

5 Wind fields observed by WINDAS

Tangential and radial wind of each site are shown in Fig.7 and Fig.8, respectively.

STAGE1:Naze As the distance of the closest place of approach (DCPA) in Naze was 84.5 km, observation data within the distance cannot be observed. The strongest peak of cyclonic wind (more than 52 m/s) concerned with frictional convergence are seen in the distance 120–150 km (in 0.5–2 km altitude) from TC center in front side and in the distance 120–130 km (in 1–2 km altitude) in the rear side of TC. In both sides of TC within 300 km, cyclonic wind tilt outward with height(see Fig.7a). Inflow is observed in almost all altitudes in front side and strong inflow (more than 24 m/s) is observed in the distance 100–250 km (below 1 km altitude) in the front side of TC. The strong peak of inflow is nearly consistent with strong peak of cyclonic wind. On the other hand, outflow is observed in all region but in the distance 100–300 km (below 2 km altitude) in the rear side of TC (see Fig.8a).

STAGE2:Kumamoto The strongest peak of cyclonic wind (more than 40 m/s) is seen in the distance 140–220 km (in 2.5–4.5 km altitude) from TC center in front side of TC(see Fig.7b). On the other hand, the peak cannot be seen in the rear side. Variations of strong peak of cyclonic wind from STAGE 1 to STAGE 2 correspond to the variations of precipitating cloud, that is, the eyewall became vague and strongest peak of cyclonic wind moved to the location of spiral rain bands. Inflow of more than 12 m/s is observed in all distances below 2 km and in all altitudes within 80 km. Especially, strong inflow of more than 24 m/s is observed in the distance from TC center to 350 km (below 1 km altitude) in the front side (see Fig.8b). We consider that a cause of intensifications and expansions of inflow of lower altitude in front side form STAGE 1 to 2 is conversion from tangential component to radial component owing to the surface friction. Through all regions of the rear side of TC, outflow is observed. We suggest that development of precipitating cloud in the rear side was suppressed because of the disappearance of inflow of the lower layer in rear side.

STAGE3:Tottori The strongest peak of cyclonic wind (more than 40 m/s) is seen in the distance 120–300 km (in 1.5–3.5 km altitude) from TC center in front side of TC(see Fig.7c). On the other hand, the peak cannot be seen in the rear side. We suggest that expansions of the strongest peak of cyclonic wind in front side from STAGE 2 to 3 is consistent with the disappearance of spiral rain bands and the expansions of strong precipitating cloud in the front side. We can see inflow in the rear side which could not be seen in STAGE 2 (see Fig.8c). We consider that variations of inflow from STAGE 2 to 3 is not relevant to the variations of precipitating clouds but relevant to the topography.

STAGE4:Muroran As strong peak of cyclonic wind cannot be seen in both sides of TC and cyclonic wind is stronger in the rear side than in the front side (see Fig.7d), structures of tangential wind in Muroran is different from the characteristics of TC. Strong outflow more than 12 m/s is observed in the distance 300–500 km (below 4 km altitude) in the rear side and inflow more than 8 m/s are observed within 100 km in both sides of TC. These structures of radial wind are also different from the characteristics of TC.

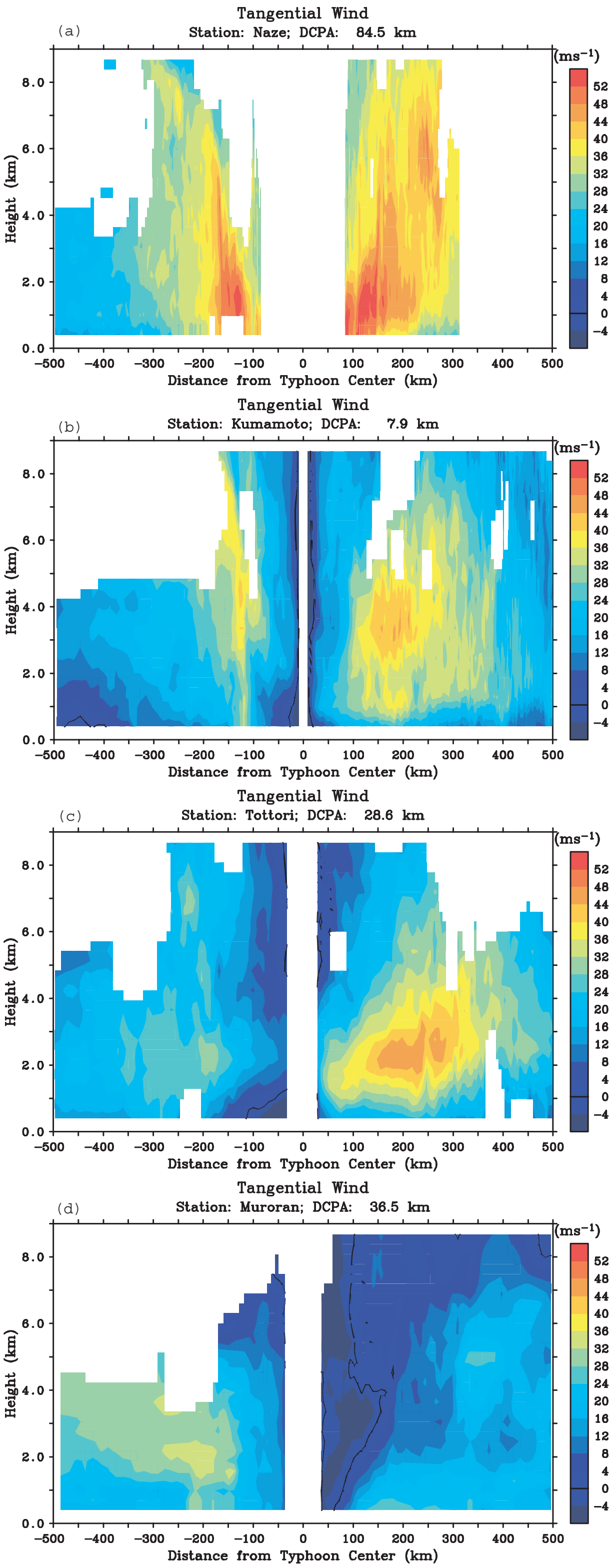


Fig.7: Radius–height cross sections of tangential wind relative to TC center at (a)Naze, (b)Kumamoto, (c)Tottori and (d)Muroran observed by wind profiler. The positive and negative values of radius correspond to the period when the TC approaches (in front side of TC) and leaves (in rear side of TC) to the observation sites, respectively. Positive and negative values of contour represent cyclonic and anticyclonic wind, respectively.

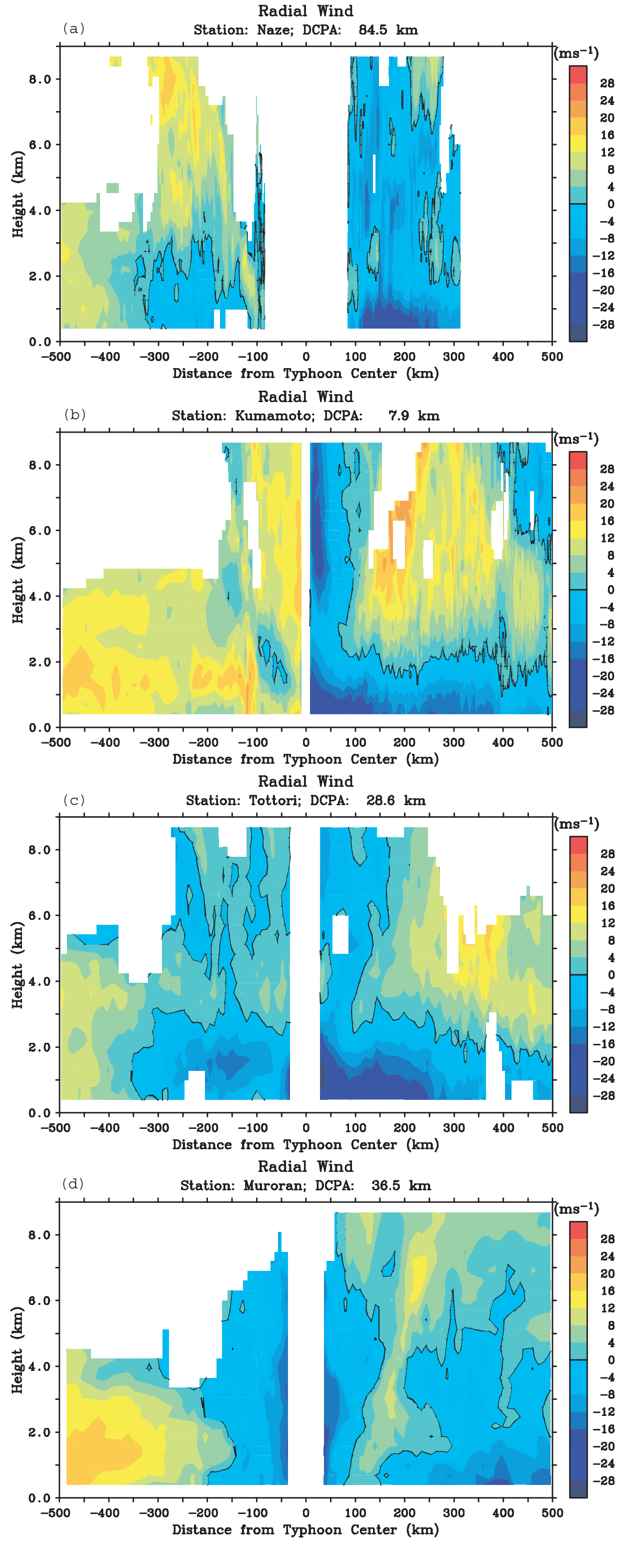


Fig.8: Same as Fig.7 but for cross sections of radial wind. Positive and negative values of contour represent outflow and inflow, respectively.

6 Summary

Based on the structural variations of precipitating clouds observed by JWA weather radar, transition process of TC, (Typhoon 0416) which passed over the Japanese Archipelago, was classified into four stages and the structures and variations of thermal and wind characteristics in the vicinity of TC center analyzed. Precipitating clouds surrounding TC eye (STAGE 1) in the south sides of the main island of Japan rapidly changed in the baroclinic zone near Japan. Though TC eye became vague just after the landfall of TC center, spiral rain bands in the front side were still obvious (STAGE 2). Spiral rain bands became obscure and strong precipitating cloud move to eastern quadrant of TC (STAGE 3). Just before the extratropical transition, strong precipitating cloud rather weakened (STAGE 4). Though the strongest peak of tangential wind shifted outward and expanded corresponding to the variations of precipitating clouds, characteristics of tangential wind in STAGE 4 was different from characteristics of mature TC. On the other hand, variations of radial wind depend on the surface friction and topography rather than the weakening of TC. Remarkable in the vicinity of TC center was observed up to STAGE 3. Rather weak worm core in the vicinity of TC center was observed in STAGE 4. Dry (wet) layer is seen in lower (higher) altitude in the front side of TC and in higher (lower) altitude in the rear side of TC in STAGE 3. We consider that these structures of humidity are own characteristics of TC in the weakening stage. Though dry air intrudes from upper layer into middle troposphere, re-intensification of TC did not happen since the stable layer exists in middle troposphere. Though thermal structures in the vicinity of TC center which was slowly changed had characteristics of TC up to before the extratropical transition, precipitating clouds and wind fields in the vicinity of TC center which was rapidly changed did not have characteristics of TC just before the extratropical transition.

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