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Secondary circulation within a tropical cyclone observed with L-band wind profilers and operational weather radars

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Abstract.
In association with the passage of a Tropical Cyclone (TC) around Japan, the secondary circulation in the region from the outer side to the center was investigated in detail by two separately located L-band wind profilers and the rawinsonde observations from October 1 to 2, 2002, for the first time.

While the TC center approached the profiler stations, several rainbands associated with the TC subsequently passed. Relatively warm, moist inflow with a cyclonic rotation was observed in the lower-troposphere while the TC center approached. The inflow reached the inside of the main rainband where the updraft was observed. Above 5 km height (with temperature below 0°C), outflow and weak downdraft corresponding to falling frozen particles were observed. It is considered that the frozen particles formed precipitating clouds mainly in the outer rainband region. The continuous wind circulation transported water vapor from the lower troposphere to the upper troposphere via the vicinity of TC center.

1 Background

Wind behavior in the vicinity of the central of a Tropical Cyclone (TC) has not fully been examined by some observations and numerical models, since the observational techniques such as airborne radars and ground-based Doppler radars cannot reveal the wind characteristics under the clear-air condition. Moreover, if simultaneous observations of a TC are conducted with multiple spatially-separated wind profilers, even mesoscale disturbances within a TC and their rapid changes can also be investigated by comparing the data between the stations.

The resolutions provided by numerical simulations are not sufficient to investigate the detailed wind changes in a TC center region. The TC, Typhoon 0221 (Higos), passed across Japan on October 1 to 2, 2002, preserving its strong primary vorticity. While the TC moved along the Japan Islands, some of the wind profilers could observe the associated wind field. Especially, since there was no rain within a radius of about 100 km from the TC center at Mito (36.38 E, 140.47 N, 29 m in MSL) and Katsuura (35.15 E, 140.31 N, 12 m in MSL) stations, the circulations corresponding to the TC could be investigated only using the operational wind profiler data.

This paper describes the kinematic structure of the TC, Typhoon Higos (0221), by using various observational data on October 1 to 2, 2002. Additionally, the circulation from lower to upper heights is discussed in the context of the profilers' observations of the vertical wind motion as well as the horizontal wind components.

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2 Observation data

The two L-band (1.3 GHz) wind profilers, parts of WINDAS (Wind profiler Network and Data Acquisition System; Ishihara and Goda, 2000; Ishihara et al., 2003) of the Japan Meteorological Agency (JMA), are able to show the wind field from the outer rainband to the storm center in detail. We used the two wind profilers' data because the two profilers observed not the orographic rainbands, but the TC associated ones. Moreover, operational C-band (5.6 GHz) meteorological radar and radiosonde data are used to show the relationship between wind behavior and rainbands.

A topographic map around the Kanto Plain in the eastern Japan, and the locations of the two profilers (Mito and Katsuura) and a radiosonde station (Tateno) are shown in Fig. 1. The Kanto Plain, whose area is about 150 km×150 km, is surrounded by mountains on the west and north sides.

The horizontal wind velocity relative to a TC center on the surface is examined by the speed of the TC movement estimated from the spline interpolation of the locations of the TC center, which were reported by JMA every one or three hour(s). Then, the horizontal wind is applied to the

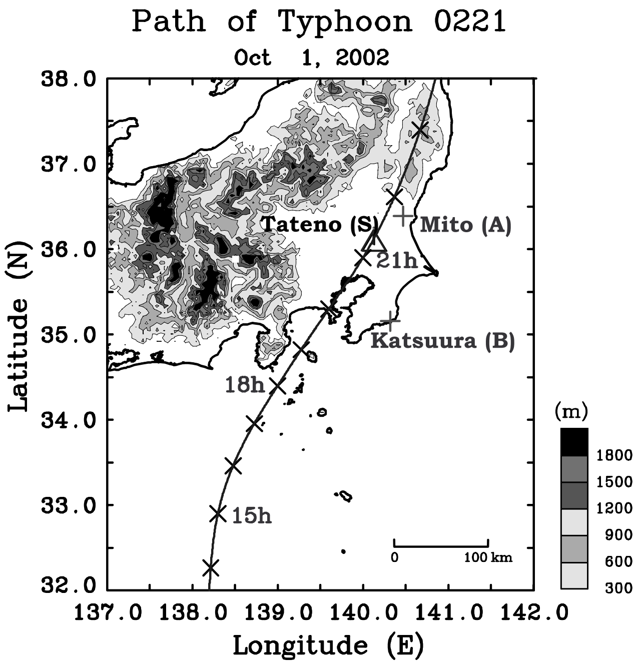

Fig. 1. The trajectory of TC Higos (0221). Cross (×) signs indicate the position of the TC center every hour. Plus (+) and triangle (△) signs indicate the positions of the two WINDAS stations and the radiosonde observatory, respectively. The distance and time of the TC center closest to Mito (A) WINDAS station were about 13 km and 21:40 LT, respectively. In the case of the Katsuura (B) station, the distance and time of closest approach were 80 km and 20:10 LT, respectively. The Tateno (S) radiosonde station was located about 50 km southwest of Mito (A). A topographical map around the Kanto plain is also indicated.

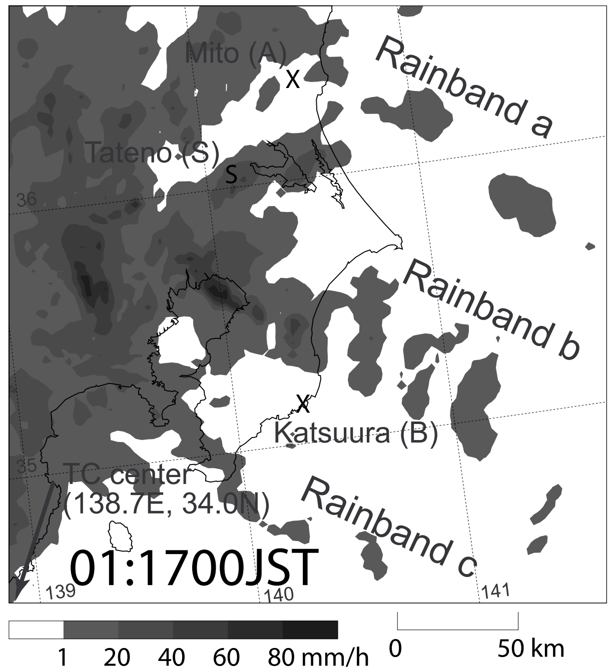

Fig. 2. C-band radar reflectivity at the 2 km level in the Kanto Plain observed at 17 LT. The main rainbands associated with the TC are also shown.

cylindrical coordinates relative to the TC center, and decomposed into the radial and tangential wind components.

3 Synoptic situation and rainband distribution

The moving path of the TC is shown in Fig. 1. The TC came from the south of Japan, and moved to the north. The profiler stations concerned with this study are located on the flat plain (as shown in Fig. 1), and the southeasterly wind in approaching the TC is mainly observed, where the wind blows from the ocean. Therefore, the observed echoes were not affected or forced by mountains, but caused by the TC.

The rain distribution in Fig. 2 shows three distinct rainbands on the eastern side of the outer and inner rainband (the northeast quadrant of the TC center). A part of so-called "Delta Rain Shield" (Willoughby et al., 1984) is distributed widely in the west of the Kanto plain.

4 Characteristics of storm-relative wind behavior

Radius-height cross-sections of signal-to-noise (SN) ratio (referred to as "echo intensity") of the vertical beam, vertical wind, storm-relative radial and tangential wind components are used in Figs. 3 and 4 to investigate wind changes associated with the TC and rainbands. The distance closest to the TC center approach at Mito and Katsuura is about 18.5 and 64.5 km, respectively. Therefore, the wind behavior within the distance cannot be observed. A positive (negative) value of the radius of the TC center means that the TC approaches (leaves) the respective stations. The period during which the TC approaches and leaves the stations are referred to as the period "in the front side" and "in the rear side", respectively. Characteristics of the wind changes during the passage of the rainbands are analyzed in the Regions labelled 1–3. The fluctuating components of the horizontal wind relative to the TC center are included of the time change of the TC as well as the asymmetric structure.

The main rainbands passed Region 1, one after another, and seemed to consist of convective precipitating clouds because strong reflectivity echo extended vertically. Figure 3c indicates that inflow and outflow are seen below and above 2 km height, respectively, while the TC was approaching the radar site. Cyclonic winds gradually became stronger in time over both stations, and, in particular, the horizontal gradient of the cyclonic wind was large in the main rainbands. As shown in Fig. 3, the maximum cyclonic wind was seen in the inner edge of Region 1 during the period 19 to 21 LT, especially below 3 km height. The strong radar reflectivity in Region 1 was associated with the large precipitating particles and the developed (or developing) clouds. Above 5 km height, where relatively strong echos were observed and the temperature was below 0°C, weak downdraft was

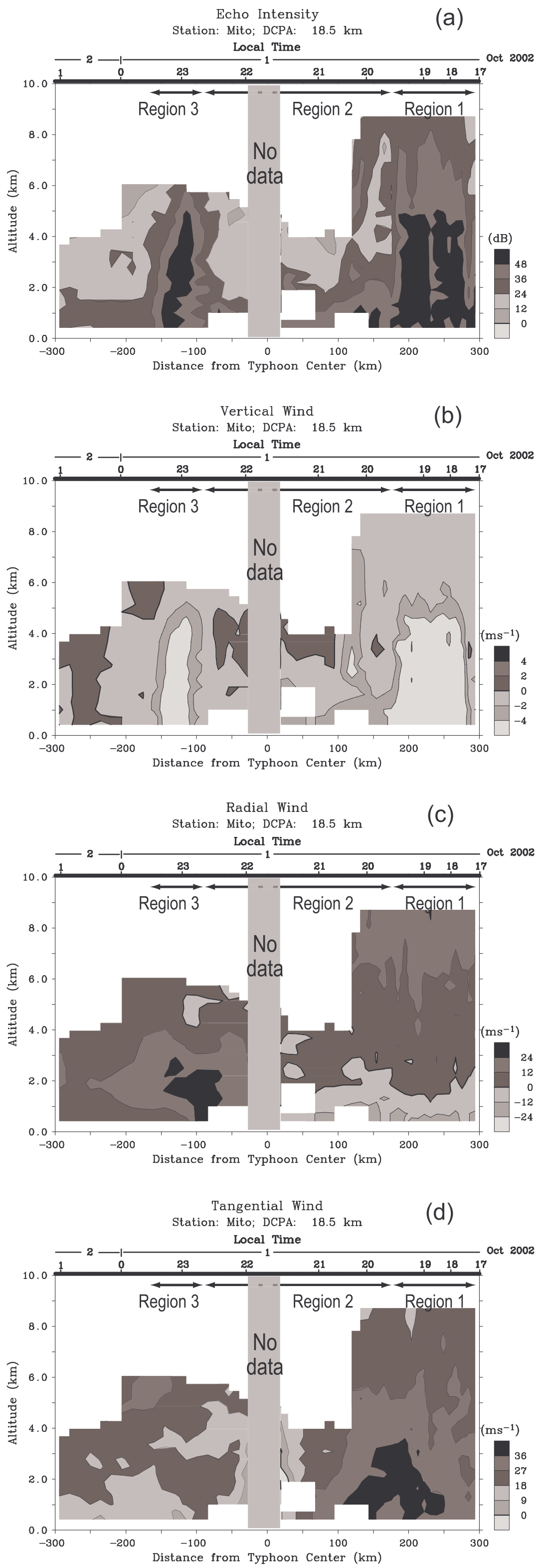

Fig. 3. Radius-height cross-sections of (a) echo intensity, (b) vertical wind, (c) radial wind, and (d) tangential wind components at Mito (A) station. Positive values of vertical, radial, and tangential wind indicate updraft, outflow, and cyclonic wind, respectively. A positive (negative) value of radius of the TC center corresponds to the period when the TC approaches (leaves). There is no data observed within 18 km in distance because the distance is that the TC approached closest to the observatory.

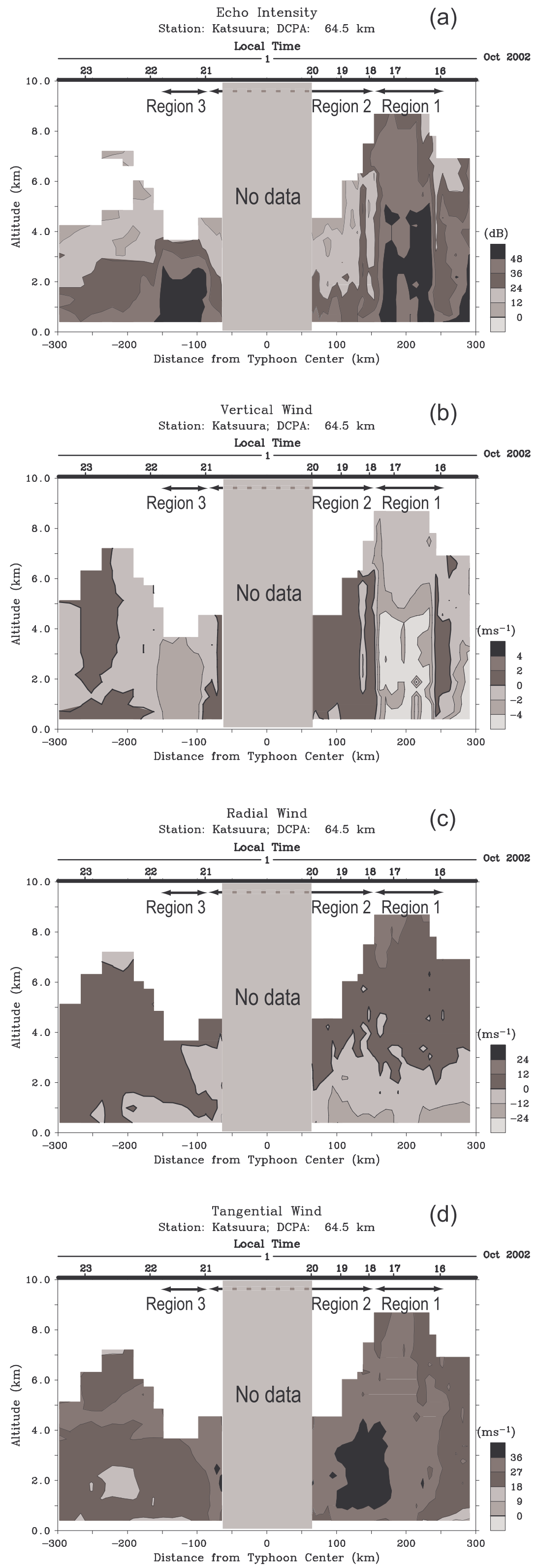

Fig. 4. Same as Fig. 3 but for the results at Katsuura (B) station. There is no data observed within 65 km in distance.

also observed. This may show that small frozen particles fell down or weak downdraft existed there. These characteristics are also seen at Katsuura in Fig. 4, especially when relatively strong inflow and the cyclonic wind were caused by the strong TC circulation.

After the passage of the main rainbands (Region 2), the cyclonic wind was quite weak relative to that in Region 1, and as shown in Fig. 3, a weak cyclonic wind was found. Particularly within about 30 km from the TC center, a weak cyclonic and radial wind was observed. Weak updraft and downdraft was clear above and below 3 km height, respectively. On the other hand, at Katsuura (B) station (Fig. 4), a pronounced updraft was seen in all layers below 6 km height. This updraft was stronger than that at Mito (A), which was also associated with strong vorticity. In Region 2, echo intensity was weak relative to that in Region 1, so there was little rain. The operational weather radar of JMA also observed little rain around Mito, Katsuura, and Tateno stations in Region 2. A saturated but stable layer existed below the 3.2 km level, judging from θ_e and θ_e^* profiles in Fig. 5a, which was obtained by the radiosonde observation at Tateno and located in about 20 km in the front side of the TC. Therefore, an updraft in Region 2 was made by not the convection, but the TC. Even if an updraft existed and the humidity was high, because the thermal stratification was stable, clouds in Region 2 were not developed. On the other hand, a high humidity layer was observed in almost all layers. Therefore, an updraft transported water vapor from the lower height to the higher.

To summarize the TC structure in its front side, both comparison between these two stations and association of the wind changes and the in-situ profiles of temperature and humidity made it clear that the updraft in Region 2 played an important role for transportation of the moist air from the lower layer to the upper layer. It was also revealed that the moist air was transported from the outside region with inflow in the lower troposphere to the outside with outflow in the middle and upper troposphere. It is considered that the rainfall in the front side of the TC was caused by falling frozen particles from the upper-troposphere, which were transported from the inner side of the TC. That circulation was stronger at Katsuura (B) station than that at Mito (A) station because of the strong TC vorticity.

5 Concluding remarks

The two wind profilers' and rawinsonde observations regarding the TC, Typhoon Higos (0221) made it clear that water vapor was continuously transported from the lower troposphere to the upper troposphere, and that the stronger the TC vorticity was, the stronger the secondary radius-height circulation was. While the TC approached, convective precipitating clouds passed successively over the station that was located in the north side of the TC. At the same time, relatively strong inflow and outflow were observed in the lower troposphere and upper troposphere, respectively. In particular, outflow and weak downdraft were seen above 5 km height.

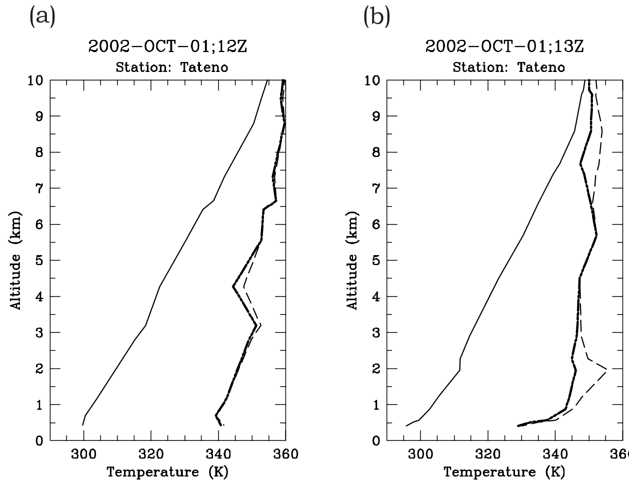

Fig. 5. Vertical profiles of potential temperature (θ; solid), equivalent potential temperature (θ_e; bold), and saturated equivalent potential temperature (θ_e^*; dashed) at Tateno (S) station at (a) 21 and (b) 22 LT on October 1. The distance from the TC center to (a) and (b) was about 20 km in the front side and 80 km in the rear side, respectively. The small difference of θ_e and θ_e^* at every height indicates the high humidity.

The latter was associated with falling of frozen particles. This means that the rainbands in the front side of the TC were formed from the rain particles coming from the TC center region.

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