NOTES AND CORRESPONDENCE

Vertical Structure of Misocyclones along a Narrow Cold Frontal Rainband

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Abstract

Five misocyclones occurring along a narrow cold frontal rainband (NCFR) were detected by single, X-band Doppler radar at Yokosuka, Japan on April 20, 2006. Each of the misocyclones, which formed in succession in the core and gap regions of the meandering NCFR over a period of 30 minutes, had a short lifetime. Three of the five misocyclones generated near the surface and reached altitudes of up to 4 km ASL. The diameters of the lower-level misocyclones increased with altitude and vorticity in the order of $10^{-2}\text{s}^{-1}$ was observed near the surface. Two of the five misocyclones had similar diameters and vorticity, and at more than 6 km ASL. One of the observed misocyclones was related to the tornado in Fujisawa and as a non-supercell type tornado within the NCFR. This tornado-related misocyclone had the largest vorticity ($5 \times 10^{-2} \text{s}^{-1}$) near the surface (300 m ASL) and was characterized as having the reduced diameter below the cloud base, which is considered typical of a tornado.

1. Introduction

The narrow band of precipitation associated with cold fronts (Narrow Cold Frontal Rainband (NCFR); Hobbs and Persson 1982), can cause a marked increase in the gradient of equivalent potential temperature and has a density structure similar to a gust front and is considered characteristic of thunderstorms (Browning 1986). In addition, areas where the wind direction changes at the NCFRs may promote the development of a tornado (Carbone 1982, 1983). Hobbs and Persson (1982) described the characteristics of a lower layer NCFR in which horizontal shear instability resulted in the formation of a horizontal shear that caused radar echoes to meander.

Recently, several observational studies and numerical simulations of NCFRs have been undertaken (e.g., Wakimoto and Bosart 2000, Jorgensen et al. 2003, Friedrich et al. 2005, Arnott et al. 2006), to make clear fine structures of NCFRs. Given that some circulations are smaller than mesoscale disturbances, the use of mobile radar and multiple Doppler radar systems has been increasingly employed to accurately capture mesocyclone development (e.g., Wakimoto et al. 2006). However, despite employing such technology, relatively fewer Doppler radar observations of the occurrence and spatial characteristics associated with tornado development of along an NCFR have been conducted to date. Using radar observations, Kobayashi et al. (2007a) described a tornado that formed in the NCFR from a parent mesocyclone having a diameter of 2 km and a vorticity in the order of $10^{-2}\text{s}^{-1}$.

In Japan, supercell tornadoes accompanying mesocyclones in the parent cloud have been reported (e.g., Niino et al. 1993; Kobayashi et al. 1996). Although tornadoes have been observed in association with a variety of weather conditions, including extratropical cyclones, typhoons (e.g., Suzuki et al. 2000), winter monsoon (Kobayashi et al. 2007b) and upper-level cold air (Sugawara et al. 2003, Friedrich et al. 2005, Arnott et al. 2006), to make clear fine structures of NCFRs.
and Kobayashi 2008), no detailed investigations of tornadoes or misocyclones being generated in NCFRs have been reported to date.

The relationship between misocyclones and tornado vortices is considered central to clarifying the mechanisms of tornado generation. However, given the relative difficulty associated with scarcity of tornadoes combined with the small-scale of misocyclones (< 4 km), few reports of tornado-related misocyclones have been published in the literature. Nonetheless, it is important to clarify where misocyclones occur in the core and gap regions of NCFRs, so that their formation can be better understood. In this paper, the vertical structure of the misocyclones generated along an NCFR occurring on April 20, 2006 is described.

2. Observations

The Doppler radar system of the National Defense Academy (NDA radar) at Yokosuka City was used in this study. The NDA radar had the following specifications: a frequency of 9.7 GHz, a wavelength of 3 cm, a beam width of 1°, a minimum detection signal of 16 dBZ, a radial resolution of 125 m, Nyquist velocity of 16 ms⁻¹, and an antenna scan rate of 6 rpm. Observations were conducted using plan position indicator (PPI) volume scans (21 elevations from 0.5° to 20.5°) and range height indicator (RHI) scans (azimuth of 355°) at 8-minute intervals. Fujisawa City is located approximately 25 km from the NDA radar site in Yokosuka (Fig. 1), and a tornado was observed over Fujisawa at the passage of the NCFR (Kobayashi et al. 2007a).

Some of the non-supercell tornadoes observed in Japan have been reported to be accompanied by misocyclones measuring several km in diameter near the cloud base (e.g., Kobayashi et al. 2007b, Sugawara and Kobayashi 2008). Provided they occur in close proximity to the Doppler radar (within 20~30 km), such misocyclones can be detected using volume scans of single Doppler radar. Since the spatial resolution of the NDA radar was approximately 400 m above Fujisawa City, it was possible to assess the structure of the misocyclones in this study.

Generally, tornado-associated misocyclones are characterized as having relatively smaller diameters and shorter lifetimes compared to mesocyclones associated with supercell thunderstorms in Japan (e.g., Kobayashi et al. 1996). Tornado vortex signature patterns have frequently been detected in parent clouds of thunderstorms with tornadoes by Doppler radar (Donaldson 1970). In the event that such circulation systems have diameters less than 4 km, then the vortex should be referred to as a misocyclone (Fujita 1981). In this study, misocyclones are defined as having vorticity greater than 10⁻² s⁻¹ and occurring at least successive three elevations.

In order to analyze mesoscale surface weather conditions, we used Automated Meteorological Data Acquisition System (AMeDAS) data (temperature, wind direction and wind velocity) combined with meteorological observation data obtained from the Japan Meteorological Agency (JMA). The data also included elements such as relative humidity, pressure, temperature, wind direction and wind velocity.

3. Vertical structure of misocyclones in the NCFR

Figure 2 shows the pressure, equivalent potential temperature, and wind fields at 12:00 JST in the study area within the radar range. At that time, a strong, uniform, southerly wind measuring approximately 10 ms⁻¹ was observed near the coast. Although marked differences in wind direction were
observed in the coastal area, the wind direction on the eastern and western sides of the NCFR (bold line in Fig. 2) were only slightly different. Conversely, the 321 K-equivalent potential temperature contour (dashed line in Fig. 2) became aligned with the cold front in a north-south direction, and a marked change in the equivalent potential temperature between the pre- and post-frontal areas was observed. It is likely that the cold front, accompanied by a short period of rainfall (~10 mm per 10 minutes, Fig. 5 of Kobayashi et al. (2007a)), wind gusts (~25 ms\(^{-1}\)) and marked elevation in pressure (~1 hPa)—all of which were observed by public institutions in Yokohama City close to where tornado damage was most extensive—maintained this very narrow strong potential temperature gradient.

Figure 3 shows Constant Altitude PPI (CAPPI) images at 1 km AGL from 11:52 to 12:22 JST. The band-shaped radar echo accompanied by the cold front was approximately straight at 11:52 JST (Fig. 3a), moving eastward at approximately 60 kmh\(^{-1}\). Each cell of the front measured approximately 10 km in diameter and moved northeastward. At 12:02 JST (Fig. 3b), the echo meandered in places along the length of the NCFR, and two or more core and gap echo patterns appeared in the meandering area of the band at 12:12 JST (Fig. 3c). Of particular interest was the appearance of a strong echo exceeding 32 dBZ along the meandering line echo pattern, with a hook-shaped radar echo forming in the NCFR when the strong echo region passed over Fujisawa City. The distance between these two misocyclones was approximately 20 km (MC 4 and MC 5) and 30 km (MC 2 and MC 3), which is in good agreement with the reported distance for between tornado parent vortex circulations in severe frontal rainbands (e.g., Carbone 1983).

As the cold front passed over Fujisawa City, PPI observations of reflectivity and Doppler velocity patterns obtained from the NDA radar revealed meanders and the core and gap regions in the NCFR (Fig. 4). From 11:46 JST (when the band echo entered the range of the radar) to 12:12 JST, five misocyclones were observed at different altitudes and times in the core and gap regions of the meandering NCFR. In the area of the meandering NCFR, peak positive and negative Doppler velocities corresponded to the core and gap regions of the NCFR, respectively. Misocyclone No. 1 (MC 1) was first detected at 11:46 JST (EL = 14.5°, Fig. 4a), MC 2 (EL = 0.5°, Fig. 4b) and MC 3 (EL = 14.5°, Fig. 4c) were observed at 11:52 JST and 11:56 JST, respectively, MC 4 is the vortex over Fujisawa City shown in Fig. 7 of Kobayashi et al. (2007a), and MC 5 is the vortex shown at 12:12 JST (EL = 1.5°, Fig. 4d). The altitude of the misocyclones ranged from 6.6 to 7.9 km ASL (MC 1), 0.5 to 3.8 km ASL (MC 2), 0.3 to 2.0 km ASL (MC 4), and 0.8 to 1.6 km ASL (MC 5). Three misocyclones (MC 2, MC 4, and MC 5) were observed near the surface, while the other two misocyclones (MC 1 and MC 3) were observed at relatively higher altitudes. Average vorticity was: 2.7 × 10\(^{-2}\) s\(^{-1}\) (MC 1), 0.9 × 10\(^{-2}\) s\(^{-1}\) (MC 2), 1.0 × 10\(^{-2}\) s\(^{-1}\) (MC 3), 2.4 × 10\(^{-2}\) s\(^{-1}\) (MC 4), and 1.3 × 10\(^{-2}\) s\(^{-1}\) (MC 5), respectively. After 12:30 JST, the decrease observed in the echo intensities of each cell meant that none of the misocyclones could be detected thereafter.

Figure 5 shows spatial distribution of the misocyclones, which, with the exception of MC 4, formed over Sagami Bay. The lifetimes of the misocyclones were as short as the interval between one radar volume scan (~8 minutes). At the lowest observed
Fig. 3. Time sequence of CAPPI images (intensity) at 1 km AGL. (a) 11:52 JST, (b) 12:02 JST, (c) 12:12 JST, and (d) 12:22 JST. Open circles denote the positions of misocyclone related core and gap region.

Fig. 4. PPI images (left EL = 1.5°) and Doppler velocity patterns (right) of four misocyclones at (a) 11:46 JST (EL = 14.5°), (b) 11:52 JST (EL = 0.5°), (c) 11:56 JST (EL = 14.5°), and (d) 12:12 JST (EL = 1.5°). The arrows show the position of the opposite peak Doppler velocities.
altitude, each misocyclone center (MC 2, MC 4, and MC 5) corresponded strongly with the gap region (weak echo) of the NCFR, and each of the misocyclones moved northeastward at approximately 60 kmh$^{-1}$. The horizontal distance between a surface tornado and the misocyclone in the clouds is often caused by the translational speed of the parent cloud (e.g., Kobayashi et al. 1996); in this case, the distance between the tornado and the misocyclone (MC 4) was 2 km above Fujisawa (Fig. 7, Kobayashi et al. 2007a).

Figure 6 shows a time-height section of the misocyclones in the NCFR. Three of the five misocyclones (MC 2, MC 4 and MC 5) generated near the surface, with MC 4 being the Fujisawa tornado-related misocyclone, which had a diameter of 1.8 km at 0.3 km ASL and 3.1 km at 1.5 km ASL. The other misocyclones (MC 2 and MC 5) had similar or more increasing diameters. The diameter of each misocyclone increased with altitude; MC 4 and MC 5 existed below 2 km ASL, while MC 2 extended up to 4 km ASL. MC 4—the Fujisawa tornado—had a maximum vorticity of

Fig. 5. The horizontal distribution of five misocyclones in the NCFR. The size of circles shows the order of vorticity, and the numbers correspond to the generation time. The star indicates the position of the NDA radar.

Fig. 6. Time-height cross section of misocyclones in the NCFR. The size of the circles denotes the vorticity (solid circle) and the diameter of the misocyclones (open circle). The misocyclone of No. 4 (MC 4) corresponds to the Fujisawa tornado. The misocyclones of MC 4 and MC 5 were observed in the same volume scan from 12:12 JST.
4.9 × 10⁻² s⁻¹ at 0.3 km ASL, which was greater than those of the other misocyclones near the surface (5.0 × 10⁻³ to 1.0 × 10⁻² s⁻¹). The observed decrease in the diameter of the misocyclones below the cloud base was considered to be indicative of increase in the potential for tornado formation. The vorticity of MC 2 and MC 5 was approximately uniform in all altitudes with no largest values being observed further away from the surface. It was not known whether the other misocyclones spawned tornadoes, as those events would have occurred over the sea where there is no evidence of tornado damage or evidence of funnel clouds.

Two of the five misocyclones (MC 1 and MC 3) formed at altitudes of 6 to 8 km ASL, and the diameters of these upper-level misocyclones did not change as markedly those of the tornado associated with MC 4. Rather, the diameter (1 to 2 km) and vorticity (on the order of 10⁻² s⁻¹) characteristics of these upper-level misocyclones were most similar.

4. Summary

Five misocyclones occurring along a narrow cold frontal rainband (NCFR) were observed using single X-band Doppler radar in Yokosuka, Japan on April 20, 2006. Each misocyclone formed in the core and gap region of the meandering NCFR and had lifetimes spanning less than one volume scan (~8 minutes). Three of the five misocyclones generated near the surface and reached altitudes of up to 4 km ASL, with the diameter of these lower-level misocyclones being observed to increase with altitude. The vorticity of the misocyclones near the surface was observed to range between 5 × 10⁻³ to 5 × 10⁻² s⁻¹. The two misocyclones that formed at altitudes exceeding 6 km ASL were similar in diameter (1 to 2 km) and vorticity (on the order of 10⁻² s⁻¹).

One of the misocyclones was related to the tornado in Fujisawa, which was a non-supercell type tornado that occurred within the NCFR (Kobayashi et al. 2007a) and had the largest observed vorticity (4.9 × 10⁻² s⁻¹) near the surface (300 m ASL). As with tornado cases, the diameter of the misocyclone decreased below the cloud base.

The five successive misocyclones generated in different locations within the NCFR over a 30-minute period could be referred to as a family of misocyclones and their occurrence implies that several tornadoes can form simultaneously along a NCFR. In addition to not knowing how lower-level misocyclones touch down as tornadoes, the relationship between upper-level misocyclones and surface-generated tornadoes is currently not well clarified. More specifically, while the application of observed vorticity values to the determination of threshold values for tornado generation is also poorly developed, this information is likely to be useful for predicting the occurrence of tornadoes.

Tornadoes are capable of causing extensive damage on a national scale in Japan. This became particularly apparent in 2006 when there was a high frequency of tornadoes, including the F2 tornado, which generated at the same time as typhoon T0613 in Nobeoka City in Miyazaki Prefecture on September 17, and the F3 tornado, which generated in Saroma-cho in Hokkaido on November 7. Approximately 20 of the tornadoes that occur across Japan annually cause damage (e.g., Niino et al. 1997), and there are numerous instances where damage is considered minor and goes unreported. In addition, observations misocyclones and tornadoes is complicated by their short lifetime and small scale, and also because their formation is not restricted to the horizontal shear zone of the NCFR. Additional research is therefore required to investigate the structure of tornadic misocyclones, with particular emphasis on the various criteria associated with tornado generation from misocyclones.

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