Single- and Dual-Doppler Radar Analysis of Misovortices within Snowband in Japan Sea Coastal Region on 17 January 2017

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Abstract

The characteristics and finescale evolution of misovortices within a snowband were examined using low-level high-resolution single- and dual-Doppler radar analysis. From 02:00 to 06:00 JST on 17 January 2017, many misovortices developed within three snowbands in the Japan Sea coastal region. The vortices developed along the shear line between the offshore north-northwesterly and the coastal northeastern. As discussed in several previous studies of misovortices along airmass boundaries, horizontal shear instability was considered to be a possible mechanism responsible for misovortex formation. A detailed investigation was performed on the most distinct snowband and misovortices embedded within it. Dual-Doppler analysis revealed a detailed behavior of vortex during merger, such as the morphological change from quasi-circular to elliptical shape, and the counterclockwise rotation which caused high-amplitude inflection of the shear line in less than 10 minutes. During the decay stage, the vortices weakened along with weakening convergence. The results suggest that evolution of the misovortex appears to have been closely tied to the low-level convergence within the vortex.

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1. Introduction

Misovortices (vortices with diameters of 40 m to 4 km) are known to develop along various kinds of airmass boundaries such as cold fronts (e.g., Carbone 1983), gust fronts (e.g., Friedrich et al. 2005), drylines (e.g., Marquis et al. 2007), and sea-breeze fronts (e.g., Kingsmill 1995). Past studies suggested that misovortices play a key role in the initiation of deep moist convection (e.g., Arnott et al. 2006) and formation of the non-supercell tornadoes (e.g., Wakimoto and Wilson 1989). Numerical studies by Lee and Wilhelmson (1997a,b) examined misocyclone development along outflow boundaries and proposed the optimal environment for strong misocycle circulation.

Past observational studies investigated three-dimensional characteristics and evolution of warm-season boundary-layer misocyclones. Friedrich et al. (2005) examined misocyclone characteristics along gust fronts in Florida with multiple-Doppler radar data. They examined the relationship between misocyclone intensity and environmental characteristics and concluded that misocyclone intensity was found to be more closely linked to the strength of horizontal wind shear. Marquis et al. (2007) examined misocyclones occurring along drylines with dual- and multi-Doppler radar analysis. They also demonstrated that the greatest average peak misocyclone intensity occurs on the same day as the greatest across-boundary horizontal shear and greatest along-boundary average of low-level convergence. Markowski and Hamon (2006) documented the evolution, structure, and dynamics of vertical vorticity extrema observed in a convective boundary layer with dual-Doppler wind syntheses. They demonstrated that the periods of vertical vorticity amplification correspond to the superposition of an updraft. They also showed that most of the vertical vorticity maxima weakened owing to weakening convergence.

Recent observational studies have revealed the presence of misovortices within winter storms or snow clouds (e.g., Kusunoki et al. 2008; Inoue et al. 2011, 2016; Onomura et al. 2017; Steiger et al. 2013; Kristovich et al. 2017), and some of them have suggested that horizontal shear instability (HSI) is the likely mechanism of vortex formation (Mulholland et al. 2017). Although specific characteristics of the evolution of larger mesoscale vortices (e.g., 50–100 km diameter) in snow events have been documented (e.g., Kawashima and Fujiyoshi 2005), the detailed structure and evolution of misovortices within snow clouds are not well understood because of the difficulty of detailed observation.

From 02:00 to 06:00 JST on 17 January 2017, under cold-air outbreaks, many misovortices developed along the shear line within the snowbands in the Japan Sea coastal region, and some of them were observed from close range by Doppler radars. We studied the fine-scale evolution of these misovortices by using low-level and dual-Doppler radial analysis at a higher resolution (~1 minute in time and ~100 m in space) than past studies in this area. The purpose of this study is to report a fine scale behavior of misovortices within snow clouds including the merger with nearby vortices and the relationship between the vorticity and low-level convergence.

2. Observation and data

We mainly used two X-band Doppler radars in the Shonai area, Yamagata Prefecture, Japan (Figs. 1a and 1b). The Doppler radar of the East Japan Railway Company (RJRE) (Fujiwara et al. 2018), has a maximum observation range of 60 km, and its radial resolution is 75 m. The antenna is 2 m in diameter, and the beamwidth is 1.2°. To observe wind gusts at high temporal resolution, the radar observes low levels (0.6°, 0.9°) continuously in plane position indicator (PPI) mode at 4 rpm. The portable X-band Doppler radar (XPOD) of the Meteorological Research Institute has a maximum observational range of 24 km, and its radial resolution is 30 m. The antenna is 1.2 m in diameter, and the beamwidth is 2.0°. The XPOD was operated in multiple PPI modes (2°, 6°, 10°, 14°, and 18°) with updates every 1 minute and the range height indicator (RHI)(285°) with updates every 3 minutes.

We manually detected vortices by identifying a Doppler velocity maximum (V\text{\text{max}}) and minimum velocity (V\text{\text{min}}) continuously in plan position indicator (PPI) mode. The vortex size and direction of rotation were recorded on each PPI scan. To estimate core diameter (D), peak tangential velocity (V\text{\text{t}}), and vertical vorticity (ζ) of a vortex from single-Doppler radar observation, we assumed a simple Rankine vortex. D was calculated by the distance between V\text{\text{max}} and V\text{\text{min}} and V\text{\text{t}} and ζ was calculated by

\[ V\text{\text{t}} = (V\text{\text{max}} - V\text{\text{min}})/2, \]

(1)

ζ = 4V\text{\text{t}}/D. \hspace{1cm} (2)

We also performed dual-Doppler analysis to derive horizontal wind fields. The data were interpolated into a 100×100-m Carte-
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on 17 January 2017, obtained from JMA mesoscale objective analysis (MANAL). The north-south oriented snowband moved southward through the observational area. The surface wind field by MANAL shows horizontal wind shear between the offshore (stronger, northerly) and the coastal (weaker, north-northeasterly) winds associated with this snowband. The surface pressure pattern was typical of winter monsoon (not shown).

From the time-space plots (Fig. 2) of wind speed, wind direction, RJRE reflectivity, and wind vectors obtained from dual-Doppler analysis at 7.5 km north of the XPOD for the period 02:00–05:30 JST, three north-south aligned snowbands developed within the observational area. The dual-Doppler-derived wind data also suggest that these snowbands developed in association with horizontal shear lines between the offshore (stronger, north-northwesterly) and the coastal (weaker, north-northeasterly) winds. In this study, we focused on Band 2, in which distinct misovortices were observed within the dual-Doppler analysis area.

3. Results

3.1 Synoptic situation and observed snowbands

Figure 1a shows rainfall rate by Japan Meteorological Agency (JMA) composite radar data and surface wind field at 03:00 JST on 17 January 2017, obtained from JMA mesoscale objective analysis (MANAL). The north-south oriented snowband moved southward through the observational area. The surface wind field by MANAL shows horizontal wind shear between the offshore (stronger, northerly) and the coastal (weaker, north-northeasterly) winds associated with this snowband. The surface pressure pattern was typical of winter monsoon (not shown).

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3.2 General characteristics of misovortices

As shown in the Doppler velocity and reflectivity fields for Band 2 (Fig. 3), the misovortices first appeared at the east edge of the snowband, and the reflectivity associated with the vortices intensified as they developed. The Doppler velocity field shows a distinct horizontal shear line and six misovortices along it. From RHI observation, the echo-top height was 3 km ASL and low-level convergence up to 0.5 km ASL was observed associated with the snowband (not shown). The core diameters of the misovortices were 0.8−2.0 km, peak tangential velocities were 4−9 m s\(^{-1}\), and average separation was 6.3 km.

In order to better understand the low-level horizontal wind fields, we performed dual-Doppler analysis. Figure 4a shows the horizontal cross-section of RJRE reflectivity, horizontal divergence, vertical vorticity and horizontal wind vectors at 300 m ASL derived from dual-Doppler analysis at 03:37:32 JST. The horizontal shear line, which is associated with the convergence zone, is evident between the stronger north-northeasterly winds on the west side and the weaker northerly winds on the east side. Misovortices 2 and 3 are also evident as vorticity maxima shown by the closed red contours and the associated reflectivity field showing a stepped pattern that closely resembles past observational (Fig. 3 of Marquis et al. 2007) and numerical studies (Fig. 7 of Lee and Wilhelmson 1997b). We investigated horizontal wind shear across the shear line based on the dual-Doppler derived across- and alongfront wind velocities. Because the shear line was oriented approximately north-south in this case, \(u\) and \(v\) components are regarded as across- and alongfront wind velocities. Figure 4b shows the horizontal profiles of across-front wind velocity \(u\) and its gradient \(\partial u / \partial x\) averaged in the \(y\) direction within the region shown in Fig. 4a. The width of the convergence zone, which is defined as the area having a gradient larger than 2 m s\(^{-1}\) km\(^{-1}\) in this study, is estimated to be 1 km. The estimated convergence within the convergence zone is ~0.007 s\(^{-1}\). Likewise, the width of the shear line is estimated to be 1 km (Fig. 4c). The alongfront wind difference across the shear line is estimated to be 5.9 m s\(^{-1}\), and the horizontal shear is ~0.006 s\(^{-1}\), which is similar to past observational studies of warm-season misocyclone accompanying shear lines (Friedrich et al. 2005; Marquis et al. 2007). HSI has been frequently suggested to cause vortices along wind-shear lines (e.g., Lee and Wilhelmson 1997b). Periodic vortices along the shear line and its similarity in appearance to that of Lee and Wilhelmson (1997b) suggest that HSI was a possible mechanism responsible for misovortex formation in this study.

Past studies also showed that horizontal convective rolls (HCRs) in the boundary layer may cause periodically-aligned enhanced convection and vortices along the fronts when the front was oriented nearly perpendicular to the HCRs (e.g., Wilson et al. 1992; Dailey and Fovell 1999). If HCRs developed in this case, they would be oriented west-east and thus nearly perpendicular to the fronts, because the wind shear below 3 km ASL was almost westerly. However, features indicative of HCRs, such as regions of enhanced reflectivity/convergence or linear pattern of Doppler velocity variation, were not observed in this case (Fig. 3). Therefore, it is possible that HSI, rather than HCRs, was the likely cause of the misovortex formation.

To understand the temporal change of misovortices, we performed a detailed investigation of the longest-lived one, vortex 2 (Fig. 3). Figure 5 shows time series of its core diameter \(D\) and peak tangential velocity \(V_t\) derived from RJRE single-Doppler analysis. Because it was difficult to identify the Doppler velocity peak couplets at the beginning and end of the profiles, the derived parameters are less reliable. The vortex exhibited a significant temporal change. From 03:18:13 JST to 03:30:53 JST, \(V_t\) increased...
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gradually, suggesting that the vortex was in the developing stage. After 03:30:53 JST, \( V_t \) began to decrease and \( D \) began to increase, suggesting vortex decay. After 03:37 JST, both \( V_t \) and \( D \) basically decreased with time, but its temporal change was somewhat complicated due to the merger with nearby weak vortices. Therefore, it was difficult to examine the behavior of vortex 2 during this period by single-Doppler analysis.

3.3 Detailed behavior of misovortices

To examine the behavior of vortex 2 in its decay stage, we performed dual-Doppler analysis. From 03:37:32 JST to 03:44:33 JST, vortex 2 and nearby weak vortices (one to the north and the other to the south) merged (Fig. 6a). During the merger, the vorticity contours deformed from nearly circular to elliptical shape with double vorticity peak (03:37:32 JST to 03:44:33 JST) and then returned to a quasi-circular shape at 03:51:24 JST. The vortex rotated counterclockwise as it moved southward. Such behaviors of merging vortices are similar to past observational studies (e.g., Marquis et al. 2007). Vortex merger is an important process of vortex development and past 2D simulations showed that the circulation (area integral of vorticity, \( \iint \zeta \, dx \, dy \)) of a vortex can be increased by vortex merger (e.g., Dritschel and Waugh 1992). In this case, however, circulation of vortex 2 continued to decrease during the merger, possibly because the nearby vortices that merged with vortex 2 were weak and the vortex 2 was in its decay stage (Fig. 6b). During the merger, northern vorticity peak weakened whereas the southern one intensified (03:44:33 JST in Fig. 7a). Since convergence was maximized in the southeastern part of the vortex 2, it is possible that vorticity was locally enhanced there.

We also calculated average divergence within the vortex (region with \( \zeta > 0.01 \, s^{-1} \)) based on the dual-Doppler-derived winds (Fig. 7b). As a shear parameter, the alongfront wind difference across the shear line was also calculated by the difference between \( v \) averaged within a 1\times3-km region centered 2.5 km east...
4. Discussion

The present study revealed fine scale aspects of misovortices within the snowband including vortex merger. The misovortices first developed at the edge of the snowband and the reflectivity of the snowband intensified after the misovortices developed. It is probable that they played some role in convection enhancement as in the warm-season misocyclones (e.g., Arnott et al. 2016).

Past studies showed that vortex merger is an important process of vortex development and some of them occurred just prior to tornado occurrence (e.g., Roberts and Wilson 1995). Though the circulation of the resultant vortex from vortex merger was smaller than that prior to merger in this study, dual-Doppler analysis revealed the detailed process of vortex merger. The morphology of the vortex changed from quasi-circular to elliptical shape with double vorticity peak. The resultant vortex rotated counterclockwise and caused high-amplitude boundary inflection, which might have enhanced mixing across the shear line as in the warm-season misocyclones (Marquis et al. 2007). Such behavior during misovortex merger occurred within less than 10 minutes, so the high-spatiotemporal dual-Doppler analysis was important to examine detailed process.

As for the relationship between the vorticity and low-level convergence, the vortices observed in our study decayed along with the low-level convergence within them weakened. This is probably associated with weakening updrafts and thus weakening vortex stretching as in Markowski and Hannon (2006). They also demonstrated that the periods of vertical-vorticity amplification involve superpositioning of an updraft. Inoue et al. (2016) also showed that the vorticity of the landfalling misovortex increased in association with an intensification of low-level convergence. Since vortices that we observed within the dual-Doppler analysis area were in their decaying phase, we were unable to examine the relationship between vortex evolution and low-level convergence within the vortex. However, it is notable that the local vorticity peak was intensified at the edge of the maximum convergence area, which is possibly due to the local enhancement of vorticity by stretching there. More studies including the dual-Doppler analysis of developing misovortices are needed to better examine the evolution process and its relation to the low-level convergence. Also, sub-minute scale volumetric observations by phased array weather radar would be highly effective to better examine the three-dimensional dynamical process of misovortex evolution (Adachi et al. 2016).

5. Conclusions

This study showed fine scale aspects of misovortices within the snowband using high resolution single- and dual-Doppler radar observation. The misovortices with $\zeta$-0.03 s$^{-1}$ developed along the shear line with cyclonic shear ($\sim$0.006 s$^{-1}$) and convergence ($\sim$0.007 s$^{-1}$). It is possible that HSI, rather than HCRs, was the likely cause of the misovortex formation as in the previous studies of misovortices within the snowbands. High spatiotemporal dual-Doppler analysis revealed the detailed and complex process of misovortex merger within the snowband for the first time. The morphological change of vortex from quasi-circular to elliptical shape, and its counterclockwise rotation which caused high-amplitude boundary inflection occurred within less than 10 minutes. This study also showed that the observed vortices weakened as low-level convergence weakened, which added to the growing body of evidence that the evolution of misovortex is closely tied to low-level convergence. Further studies examining the behavior of misovortices at various life stages and in various environments would be helpful to better understand the evolution of misovortices and its relation to the environmental characteristics and low-level convergence field.

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