Rapid Intensification of a Winter Misocyclone under an Isolated Convective Cloud after Landfall

Shiho Onomura1, Kenichi Kusunoki1, Ken-ichiro Arai1, Hanako Y. Inoue1, Naoki Ishitsu1, and Chusei Fujiwara2
1Meteorological Research Institute, Tsukuba, Japan
2East Japan Railway Company, Saitama, Japan

Abstract
A wind gust of F0 scale occurred in Shonai town, Yamagata Prefecture, Japan, on 4 December 2015. It damaged some houses in a narrow valley 24 km from the coast of the Japan Sea. Around that time, one of many isolated convective clouds greater than 6 km in height traveled over the area. Observation of two Doppler radars with high resolution in time and space showed that a cyclonic vortex generated at the south edge of the convective cloud after landfall from the Japan Sea rapidly developed with increasing vorticity as it moved inland. The vortex traveled across a mountain, and its southern part near its center subsequently passed over the damaged area. The radius and vorticity of the vortex were 0.64 km (misoscale) and 0.048 s⁻¹, respectively. A hook-shaped echo, a vault-shaped echo, and a couplet of maximum and minimum Doppler velocities, which indicate the existence of a vertically oriented vortex tube, are clearly shown. This study discusses the development of the winter misocyclone observed by the radars in terms of the relationship with the behavior of the parent cloud and the possible topographical influence of the mountain and valley on the vortex structure.

1. Introduction

Winter tornadoes in Japan are often associated with convective activities caused by cold air outbreaks from the Eurasian continent over the Japan Sea (Ninomi et al. 1997). Many winter miso-scale vortices including winter tornadoes (hereafter called winter misocyclones) are generated and developed over the Sea, and travel with the monsoon to the coast. Such winter misocyclones have been found in various mesoscale cloud systems including a convective cloud developed in part of a cloud band (Kobayashi et al. 2007), a band-shaped cloud at the leading edge of a frontal zone (Inoue et al. 2011), and a locally developed snow cloud band (Kato et al. 2015). These previous studies reported changes in the structure of those vortices after landfall such as the dissipation of the vortices on land possibly caused by the effect of ground surface friction on the angular momentum of the vortices. This is consistent with the fact that damage by winter tornadoic gusts are concentrated along the coast. According to the wind gust database of Japan Meteorological Agency (JMA 2016), however, winter tornadoes often damage areas distant from the coast. The number of studies that focus on these tornadoes is few in contrast to those of tornadoes near the coast, as reviewed above.

On 4 December 2015, a wind gust occurred in a narrow valley in Yamagata Prefecture distant from the coast of the Japan Sea. In this study, two Doppler radars are used to provide unique observational data of this event with high resolution in time and space. The datasets allow for analysis of the detailed evolution and structures of a winter misocyclone and its parent cloud, which were probably associated with the wind gust. Particularly, this study presents the evolution of the misocyclone from its generation to the early stage of its decay, which has been rarely investigated in previous studies. The results are reported in comparison with the JMA damage assessment of the wind gust.

2. Overview of the JMA damage assessment

The JMA, which surveys details of disasters caused by wind gusts, reports a wind gust occurrence in Shonai town, Yamagata Prefecture, Japan, around 9:00 LST (Local Standard Time) on 4 December 2015 (JMA 2015). Damages were reported to two residential and three non-residential structures located in a north-south-oriented narrow valley with a width of about 0.5 km between mountains a few hundred meters high. The valley is located approximately 24 km from the coast of the Japan Sea and at the east side of the Shonai Plain. The strength of the wind gust was F0 scale, as surmised by visual inspection of the damaged area. However, the cause was not identified, because no wind divergence/convergence trace was found and no gust was reported by witnesses.

3. Study area and methodology

Intensive observation for winter tornadic storms has been conducted in the Shonai Plain since October 2007 (Kusunoki et al. 2008). The observation system contains two X-band Doppler radars with high resolution in time and space. These radars, hereafter referred to as JR radar and XPOD, are installed on the roof of the Amarume station 11 km east of the coast line and on the Shonai airport building near the coast, respectively (Fig. 3). The basic characteristics of the two radars are summarized in Table 1. A major difference between the two lies in the observation mode. A plan position indicator (PPI) scan for a fixed elevation of 3° every 30 s is set in JR radar. However, a PPI scan for five elevations from 2° to 18° and a range height indicator (RHI) scan for an azimuth of 105° per approximately 2 min are configured in XPOD. In this study, only the 2° PPI data and the RHI data were used for XPOD.

Moreover, the JMA composite radar data were used to analyze the echo top and 5-min rainfall intensity of a parent cloud associated with the wind gust in addition to those of the surrounding clouds.

Table 1. Basic characteristics of JR radar and XPOD, two X-band Doppler radars

| JR radar | XPOD |
|----------|------|
| Range resolution | 75 m | 30 m |
| Beam width | 2.0° | 2.0° |
| Scanning mode | PPI (elev. = 3°) | PPI (elev. = 2, 6, 10, 14, 18°) |
| RHI (azimuth = 105°) |
| Antenna rotation rate | 2 rpm | 4 rpm |
| Detectable range | 30 km | 24 km |

Corresponding author: Shiho Onomura, Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan. E-mail: onomura@mri-jma.go.jp. ©2017, the Meteorological Society of Japan.
4. Synoptic and meso-scale weather conditions

A surface weather map reported at 9:00 LST (JMA 2015), around the time of the storm occurrence (Fig. 1a), illustrates the pressure pattern typical for winter monsoon blowing toward the southeast over Japan. Around the study area (Fig. 1a, red box), a southwest-northeast pressure gradient existed. A cold air mass with the temperatures below −35°C was spread at the 500 hPa level of the atmosphere (not shown). On a meso-scale level, no characteristic disturbance was found in the atmosphere. By using the JMA local forecast model data at 9:00 LST, the possibility of supercell formation was investigated. The convective available potential energy (CAPE) was 100–200 J kg$^{-1}$ and the storm relative helicity (SReH) was 50−100 m$^2$ s$^{-2}$. These values are too low to support the formation of supercells. An infrared image captured by the Himawari-8 geostationary meteorological satellite at 9:10 LST shows that many isolated convective clouds were evenly situated over the Japan Sea (Fig. 1b). Some of these clouds traveled to Yamagata Prefecture. According to the JMA composite radar data (not shown), the echo tops of the convective clouds were mostly greater than 6 km, which is unusually high for winter convective clouds in this region.

5. Radar observation of parent cloud and misocyclone

Temporal developments of the rainfall intensity and the echo top of a parent cloud associated with the wind gust were analyzed by using the JMA composite radar data. The rainfall intensity of the cloud was first recognized over the Japan Sea about 160 km from the coast at 7:00 LST. The intensity and area increased gradually as the cloud traveled toward the coast. As shown in Fig. 2, rapid increases in intensity were observed between 8:00 and 8:30 LST and between 9:00 and 9:20 LST. The cloud passed over the damaged area at about 9:10 LST and the highest intensity occurred at 9:20 LST. Later, the intensity decreased as the cloud traveled farther toward the Pacific Ocean. When the cloud reached the Ocean at 10:30 LST, it was no longer identified in the rainfall intensity field. The echo top of the cloud (not shown) changed approximately after the variation of the rainfall intensity was noted. The height was about 3 km at 7:00 LST, after which time the echo top greatly increased and exceeded 7 km at 8:30 LST. The high echo top was roughly held until 9:30 LST. After that time, the height decreased gradually as the rainfall intensity became smaller. According to these results, the parent cloud developed as it traveled over the Japan Sea and the Shonai Plain, and reached its mature stage nearly over the damaged area with the highest rainfall intensity and echo top. Although the surrounding clouds showed a similar tendency, the parent cloud had a slightly higher intensity and echo top, particularly between 9:10 and 9:20 LST.

The JR radar data provided more detailed structure and behavior information of the parent cloud over the Shonai area. Figure 3 shows the outline of the parent cloud between 8:47 and 9:08 LST, which was determined on the basis of radar echo greater than 15 dBZ. The size of the cloud was approximately 25 × 13 km.

The cloud traveling from the Japan Sea arrived at the coast at 8:52 LST. It continuously traveled to the east across the Shonai Plain, entered the mountain region at 9:06 LST and approached the damaged area at 9:08 LST. The average translation velocity was 26.9 m s$^{-1}$. Around 8:57 LST, the south edge of the parent cloud began to cyclonically rotate in the middle of the Shonai Plain.

A time series of the JR radar echo around the rotating part (Fig. 4) illustrates that a hook-shaped echo became more pronounced as it moved inland. When it arrived nearly above the damaged area at 9:08 LST, the hook echo shows a clear doughnut shape. The southern part of the vortex near its center passed over the damaged area 1 min later. This vortex was intensified as the parent cloud developed to its mature stage. The further track of the vortex for 5 min showed that the hook shape had a tendency to collapse (not shown).

An RHI scan near the hook-shaped echo (Fig. 5) was recorded by XPOD at 9:07 LST. The vertically scanned echo shows that the depth of the parent cloud exceeded 6 km, which approximately corresponds to the echo top of the cloud observed by the JMA composite radar. The echo near the ground exhibits a vault shape of 2 km × 1 km, around which a couplet of maximum and minimum Doppler velocities was found. These characteristics and the hook shape of the radar echo prove the existence of a vertically-oriented vortex tube.

Characteristic variables of the cyclonic vortex observed by the JR radar such as peak tangential velocity, radius and vorticity between 8:58 and 9:09 LST were analyzed. In this analysis, the vortex was determined by drawing a circle through the locations of maximum and minimum Doppler velocities. The track of the vortex is depicted in Fig. 3 and 4. Peak tangential velocity ($V_t$) was calculated as one-half the difference between the Doppler velocity maximum ($V_{max}$) and minimum ($V_{min}$) and the core diameter of the vortex ($D$) was the distance between the locations of $V_{max}$ and $V_{min}$. Moreover, the vorticity was calculated as $4V_tD^{-1}$. For the time before and after the analysis period, vortices could not be determined because the pattern of the couplet of $V_{max}$ and $V_{min}$ was unclear.

As shown in Fig. 6a, during a few minutes after the vortex started to be recognized in the Shonai Plain (8:58–9:00 LST), $V_t$ increased slightly from 10.3 m s$^{-1}$. However, when the vortex subsequently traveled in the Plain, $V_t$ changed little between 9:01 and 9:03 LST and decreased between 9:04 and 9:05 LST. Thus,
Fig. 2. Time series of 5-min rainfall intensity between 8:00 and 10:30 LST on 4 December 2015, acquired from the JMA composite radar data. The red circle marks the parent cloud associated with the wind gust. The parent cloud passed over the wind gust-damaged area at 9:10 LST. The red box in the figure of 8:00 indicates the area shown in Fig. 3.

Fig. 3. Track of the parent cloud associated with the wind gust. The outline of JR radar reflectivity greater than 15 dBZ is sketched. The track of the cyclonic vortex developed under the cloud is indicated by a blue circle. The dashed-line rectangle indicates the area of the figure of 8:57 LST in Fig. 4. The locations of JR radar, XPOD, and the damaged area are marked by the black filled triangle, black filled circle, and red cross, respectively. The brownish filled contour shows the elevation.
Fig. 4. Time series of radar echo of the southern edge of the parent cloud PPI-scanned by JR radar. The vortex found between 9:00 and 9:08 LST is indicated by a black circle. In the figure of 9:08 LST, the damaged area is marked by a red cross.

Fig. 5. PPI scan (upper) and RHI scan (lower) of reflectivity of radar echo (left) and Doppler velocity (right) captured by XPOD 2 min before the vortex reached the damaged area (9:07 LST). Green straight lines indicate the RHI section or the PPI section. Vertical dashed lines show the center of the vortex.

Fig. 6. Development of (a) peak tangential velocity ($V_t$), (b) radius and (c) vorticity of the vortex calculated from the JR radar data as it traveled over the Shonai Plain and the mountain area. The center of the vortex was closest to the damaged area at 9:09 LST. The gray area shows height above sea level along the path of the vortex; the time of its passage is indicated at the top.
no clear tendency of \( V_r \) was observed. On the contrary, the radius of the vortex \((D/2)\) decreased consistently from 1.3 km over the Shonai Plain (Fig. 6b); thus, the vorticity tended to increase from 0.015 s\(^{-1}\) in the Plain (Fig. 6c). When the vortex moved over the mountain and valley (9:06−9:09 LST), \( V_r \) gradually increased and reached its highest level, 15.3 m s\(^{-1}\), over the damaged area. By adding this result to the average translation velocity, the maximum wind speed of the vortex at the radar measurement height of ~500 m was estimated to be 42.2 m s\(^{-1}\). This value corresponds to the F1 scale, which is higher than the F0 scale estimated through the JMA visual inspection of the damaged area. The radius changed little on the upslope of the mountain, although it decreased on the downslope and reached its minimum, 0.40 km, at 9:08 LST. When the vortex center was closest to the damaged area at 9:09 LST, the radius was 0.64 km. According to the vortex size, the cyclonic vortex is categorized as a misocyclone. With those changes in radius, no clear tendency was noted in the vorticity over the upslope, whereas the vorticity on the downslope increased significantly and the largest value, 0.070 s\(^{-1}\), was found at 9:08 LST. At 9:09 LST, the vorticity decreased to 0.048 s\(^{-1}\). These results indicate that the vortex intensified over the Shonai Plain and the mountain region reached its mature stage with the largest \( V_r \) and the large vorticity over the damaged area at about the time of the wind gust occurrence. Although these characteristic variables of the vortex could not be estimated beyond 9:09 LST, it was observed that the hook shape of the radar echo tended to collapse after 5 min, as mentioned above. This tendency could indicate decay of the vortex.

6. Summary and discussion

A wind gust occurred in a valley distant from the coast in Yamagata Prefecture around 9:00 LST on 4 December 2015. By using radar observational data, it was revealed that an isolated convective cloud traveled from the Japan Sea to the damaged area as the rainfall intensity and echo top of the cloud increased. A misocyclone with a radius of 1.3 km and vorticity of 0.015 s\(^{-1}\) was generated under the parent cloud after landfall from the Sea. The misocyclone was intensified with decreasing radius and increasing vorticity as it moved inland. Around the time at which the wind gust occurred at the ground level, the parent cloud was nearly in its mature stage, and the southern part of the vortex near its center passed over the damaged area. The radius and vorticity of the vortex were 0.64 km and 0.048 s\(^{-1}\), respectively. In addition, it was found that a vertically-oriented vortex tube exists at about the time. These results suggest that the wind gust may have been caused by a tornado-like storm that was intensified under an isolated convective cloud after landfall from the Japan Sea.

The intensification of the misocyclone after landfall is apparent in contrast to previous reports of winter tornadic vortices and misocyclones developing over the Japan Sea and dissipating after landfall (Kobayashi et al. 2007; Inoue et al. 2011; Kato et al. 2015). According to the present results, the evolution of the misocyclone is probably related to the parent cloud’s development. However, dominant mesoscale weather conditions to support the strong development of the parent cloud were not found in this study. Furthermore, although the structure of misocyclones is predominantly controlled by the conditions of the parent cloud and the near-surface tornadic vortex, the misocyclone might have been influenced to some degree by the topography when it traveled over the mountain and valley. In fact, Karstens (2012) and Lewellen (2012) address the significant topographical influences on near-surface structures of tornadoes. To clarify these questions, further studies utilizing numerical simulations should be performed.

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