• **News & Views** •

Recent Significant Tornadoes in China

Ming XUE*[1,2], Kun ZHAO[1], Mingjung WANG[1], Zhaohui LI[3], and Yongguang ZHENG[4]

[1]*Key Laboratory of Mesoscale Severe Weather/Ministry of Education, and School of Atmospheric Sciences, Nanjing University, Nanjing* 210023*, China*

[2]*Center for Analysis and Prediction of Storms and School of Meteorology, University of Oklahoma, Norman OK* 73072*, USA*

[3]*Fushan Tornado Research Center, Fushan Meteorological Service, Fushan* 528000*, China*

[4]*National Meteorological Center, China Meteorological Administration, Beijing* 100081*, China*

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1. Introduction

Compared with the United States, whose annual number of tornadoes can exceed 1000, the average number of tornadoes per year in China over the past half a century is estimated to be fewer than 100 (Fan and Yu, 2015), even though both countries are located in a similar latitudinal zone of the Northern Hemisphere. The annual average recorded number of F1 (Fujita scale) or EF1 (enhanced Fujita scale) intensity or higher tornadoes in China between 1961 and 2010 is about 21 (Fan and Yu, 2015), while that in the United States is 495 between 1954 and 2013 (Brooks et al., 2014). The number of the most intense tornadoes are even more rare in China. In fact, only five tornadoes of EF4 intensity have been recorded between 1950 and 2010, and none at F5 or EF5 intensity has been recorded. Still, when tornadoes do occur, they tend to cause extensive damage and loss of life, partly because of the dense population in the coastal regions where tornadoes occur most often. The unpreparedness of most people combined with the lack of tornado-protection facilities also plays a role. Over the 50 years starting from 1961, at least 1772 people died because of tornadoes (Fan and Yu, 2015). However, owing to their relative rarity, tornado forecasting and warnings have not been part of the operational weather forecasting requirements within China, although experimental tornado forecasting and warning operations have just begun in several provinces after a number of recent significant tornadoes.

Jiangsu Province in eastern China experiences by far the largest number of significant tornadoes (EF2 or greater) in China. Over the 50 years between 1961 and 2010, there were 36 of them on record in Jiangsu, while the next six provinces (including an autonomous city) featuring more than 10 occurrences were Hubei (15), Hunan (14), Shandong (13), Shanghai (12), Anhui (11) and Guangdong (11). Jiangsu also had eight EF3 or stronger tornadoes, while other provinces had at most two (Fan and Yu, 2015). Jiangsu Province, comprising mostly of flat terrain—especially in northern Jiangsu—and being located along the eastern coast, often experiences strong low-level southerly flows and the influence of strong midlatitude weather systems from the north in the spring and summer seasons, apparently has the more favorable conditions for tornadoes within China.

Several tornadoes of note occurred in China in the summer of 2016. The most significant occurred in the afternoon of 23 June 2016, in Funing County of Yancheng City in northern Jiangsu Province, and was rated EF4 on the enhanced Fujita scale (McDonald and Mehta, 2006). Earlier in the month, on 5 June 2016, an EF3-rated tornado occurred in the northeastern corner of Hainan Island/Province, near Fengpozhen of Wenchang City. Less than two months later, near Xiaqiaozhen, Xuwen County, Zhanjiang City of Guangdong Province, just across the Qiongzhou Strait from Hainan Island, another weak tornado occurred on 30 July 2016. Earlier, on 4 October 2015, several tornadoes were spawned within the outer rainbands of the landfalling Typhoon Mujigae (2015) in Shunde District, Fushan City of Guangdong Province. One of the tornadoes was rated EF3. These tornadoes are briefly introduced in this paper.

2. Yancheng EF4 tornado (23 July 2016)

As stated earlier, a violent tornado occurred in Funing Country, Yancheng City in northern Jiangsu Province in the afternoon of 23 June 2016. Field damage survey indicated an EF4 intensity. It occurred in a relatively densely populated area, caused 99 casualties, and injured over 800 people. This tornado became the 6th EF4 intensity tornado on record in China since 1950, and the second EF4 rated tornado in Jiangsu Province, with the last one having occurred in 1979. This tornado is so far the most extensively surveyed event of this type in China; a group of about 10 researchers from the China Meteorological Administration, Nanjing University, Peking University and the Jiangsu and Guangdong meteorological bureaus thoroughly surveyed the tornado sites over a three-day period immediately after the day the tornado

* Corresponding author: Ming XUE
Email: mxue@ou.edu

struck. Three unmanned aerial vehicles (UAVs) were employed, taking many hours of video footage and thousands of photographs of the tornado's damage.

Figure 1 shows some of the UAV aerial images. The top panel, pointing northward (west on the left and east on the right), indicates a wide tornado damage path. Figure 1b shows extensive damages to single-family farmhouses, with most of them completely flattened to the ground, although the debris mostly remains on or near the foundations, indicating EF4 damage. Figure 1c shows complete damage to a side building of a major factory (upper center — right part of the picture), while the roof of the main factory building is com-

Fig. 1. Aerial survey images showing extensive and severe damage caused by the Funing County, Yancheng City, Jiangsu Province tornado of 23 July 2016.

pletely torn away. The ground survey showed that a tree of 65 cm in diameter was snapped in the middle part of its trunk. A car was picked up and thrown more than 50 m and a full-size empty container was thrown 400–500 m from its original site (Zheng et al., 2016).

Figure 2 shows the track of the Funing tornado based on a ground damage survey. The track with EF1 and above damage starts at Banhuzhen located west-southwest of downtown Funing County, and ends at Wutanzhen, southeast of downtown Funing. The length of the track is about 33 km. About half of the track has an EF1+ damage width of 3–4 km, and the rest of the track has a width of 1–2 km. The widest location is about 4.5 km. All EF4 damage was found along the eastern half of the track.

The convective storm that produced the Funing tornado initially developed midway between Fuyang City and Bengbu City of Anhui Province, about 325 km west of Funing County, shortly before 0000 UTC [0800 LST (Local Standard Time)] 23 July, as the southernmost cell in a line of storms aligned more or less in the north–south direction (not shown). This cell evolved into one that had clear supercell characteristics after 0400 UTC (Fig. 3a). Figure 3b shows that, by 0421 UTC, a hook echo was evident in the low-level reflectivity, as pointed to by the red arrow. By 0603 UTC (Fig. 3d), this hook was even more pronounced, and there was indication of reflectivity wrap-up by 0631 UTC (Fig. 3e), indicating very strong low-level rotation at this time. By 0700 UTC (Fig. 3f), the hook echo had mostly disappeared.

Figure 4 shows the low-level measured radial velocity maps together with the identified mesocyclone track. The positive–negative velocity couplet is well defined at 0614 UTC (Fig. 4a), with the radial velocity differential being more than 40 m s^{-1}. By 0637 UTC (Fig. 4b), the mesocyclone had significantly intensified and the velocity differential between neighboring radials exceeded 60 m s^{-1}, manifesting an intense tornado vortex signature. The mesocyclone was the strongest in this radar scan volume. By 0654 UTC (Fig. 4c), the mesocyclone had significantly weakened and decreased in size, although the radial velocity differential was still as large as 40 m s^{-1}. The actual tornado is believed to have lasted between 0615 and 0700 UTC, or 1415 to 1500 LST. Despite the long life cycle and long track, there was no photograph taken of the entire funnel cloud of this tornado that we know of. This is apparently because the tornado was completely rain-wrapped, as is also suggested by the wrapping hook echo at 0631 UTC in Fig. 3. The maximum hourly rainfall at nearby rain gauge stations was about 50 mm, while hailstones of 2–5 cm were reported north of downtown Funing, matching the location of the main reflectivity core of the supercell storm (Fig. 3). A video of the eastern portion of the rotating tornado circulation with flying debris and heavy precipitation was taken at the front door of a Wutanzhen Elementary School building (Wutanzhen is near the end of the tornado track, see Fig. 1), which represents the only direct visual evidence of this violent tornado. As one of the most important tornado events in China's documented history, this

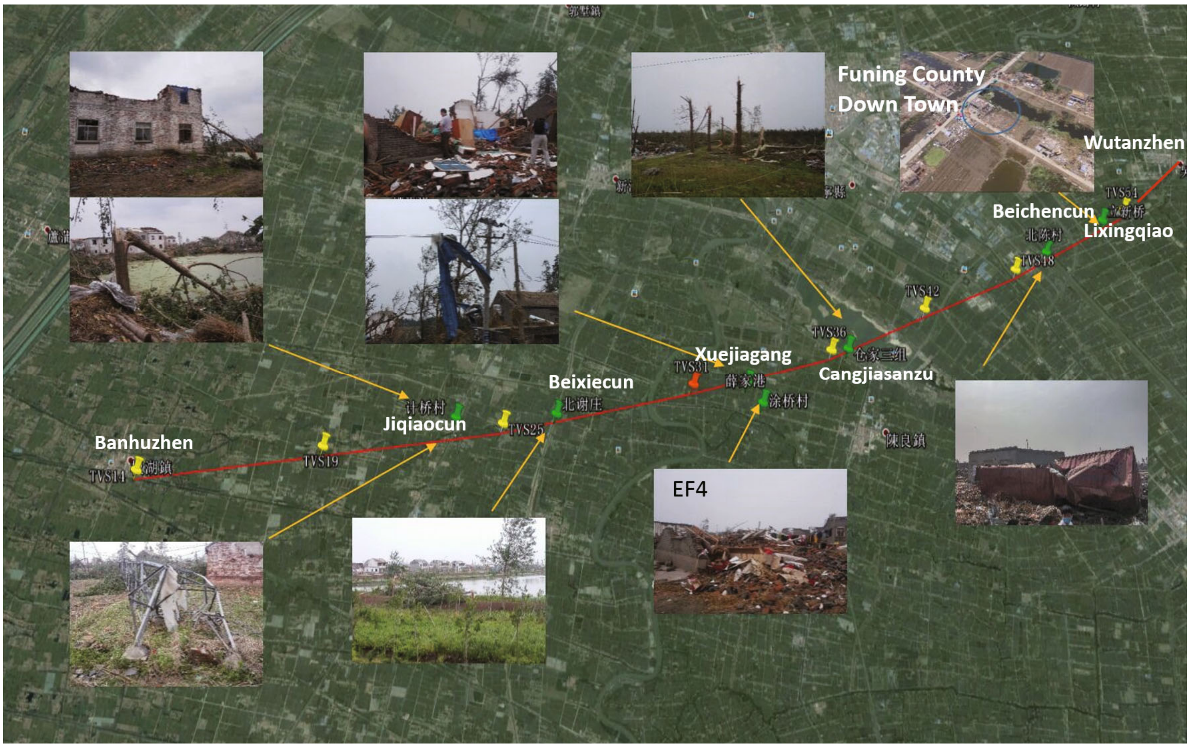

Fig. 2. The path with EF1 and above damage associated with the Funing tornado of 23 July 2016, with some of the towns and villages labeled.

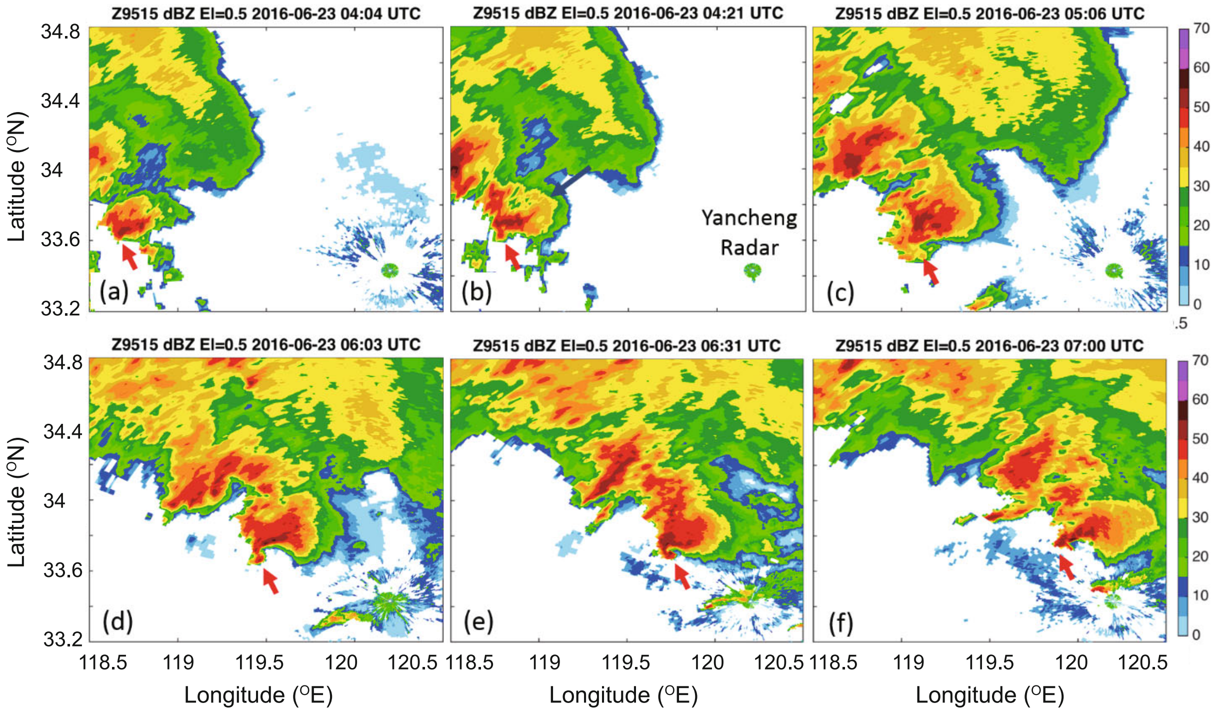

Fig. 3. Observed reflectivity at the 0.5° elevation of Yancheng operational S-band radar at the times indicated above each panel. The red arrow points to the hook echo of the supercell. The tornado was most intense near 0630 UTC (1430 LST).

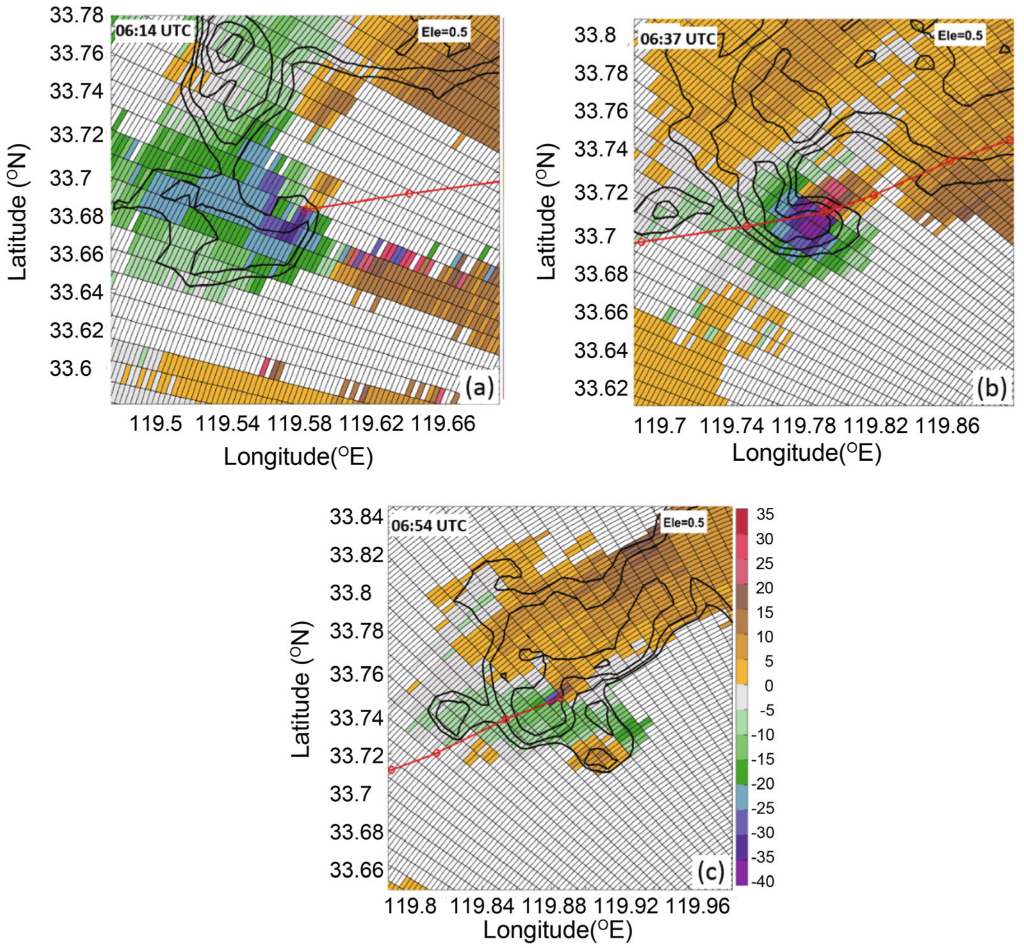

Fig. 4. Radial velocity measurements (color shading) and reflectivity contours of the 0.5° elevation Yancheng radar overlain on the identified mesocyclones (red circles) and track (red line).

case will undoubtedly receive considerable attention from researchers and operational forecasters through detailed studies.

3. Wenchang tornado (5 June 2016)

On 5 June 2016, a tornado formed at around 1512 LST near Fengpozhen of Wenchang City, Hainan Province, which is located in the northeast corner of Hainan Island in southern China, south of Guangdong Province, across the Qiongzhou Strait (Fig. 5). The tornado hit nine villages in two towns, caused one death and 11 injuries, and destroyed 178 houses. It moved in a westward direction and dissipated at around 1527 LST near Hushan Reservoir, leaving a 3.6 km damage track with an approximate 200 m width (see the red track pointed to by the red arrow near Fengpozhen in Fig. 5). Damage survey indicated an EF3 intensity (Fig. 6). The short life, narrow width, and sparse population contributed to the relatively low death and injury numbers. Initial analyses of surface observations indicated the presence of an afternoon sea-breeze front along which convection was initiated. Visible imagery (not shown) from the Japanese Meteorological Agency geostationary satellite Himawari 8 indicates cloud formation along the sea-breeze front at around 1400 LST. Then, an isolated convective cell underwent explosive growth between 1440 and 1500 LST, and its cloud anvil started to merge on its west side with anvils from a mesoscale convective system at around 1510 LST. A rather weak hook echo can be identified from the 0.5° elevation scan (not shown) of Haikou radar located about 50 km to the west (see Fig. 5). A small tornado vortex signature with a velocity differential of over 20 m s^{-1} can also be seen in the velocity field (not shown). The fact that the tornado formed about 10 minutes after the rapid intensification of the storm cell suggests that the tornadogenesis dynamics was different from that of supercell tornadoes, for which the downdraft and cold pool typically play important roles. Most likely, pre-existing vertical vorticity along the sea-breeze front (Roberts and Wilson, 1995), and possibly also the tilting of frictionally generated vorticity (Roberts et al., 2016), constituted the main sources of vorticity for the tornadogenesis, while the intense updraft accompanying the explosive storm development provided the intense low-level stretching for vortex intensification. The exact processes await further study.

4. Zhanjiang tornado (30 July 2016)

On 30 July 2016, another tornado formed near Xiaqiaozhen, Xuwen County, Zhanjiang City of Guangdong Province. The tornado is estimated to have formed shortly after 1500 LST and lasted for 7 to 15 minutes according to different witness reports. It formed over an open field near an industrial park and did not move much before dissipation. Witnesses described the tornado forming before precipitation

Fig. 5. A map showing the southern tip of Zhanjiang City, Guangdong Province, and the northern part of Hainan Island of Hainan Province. The track of Wenchang tornado near Fengpozhen, and the location of Xuwen tornado near Xiaqiaozhen, are pointed to by the red arrows, respectively. Xuwen County and Wenchang City are indicated by the pink shading.

at the ground, and pictures taken of the tornado show red-colored debris clouds (Fig. 7a), which come from the red soil of the open field. The funnel was described to have had a width of about 50 m. Because this tornado did not hit any built structures or trees, its intensity could not be properly rated, and it did not cause any human or property damage. The debris funnel does, however, suggest a significant intensity. Because the tornado formed before precipitation fell to the ground, Xuwen Country weather service suggested that it should probably be classified as a dustnado. Still, given the presence of a rapidly developing storm above, classifying it as a tornado is more appropriate.

Analyses of surface station data indicate the presence of a roughly north–south oriented sea-breeze frontal boundary

Fig. 6. Photographs of Wenchang tornado funnels and damage to a farmhouse and tall trees.

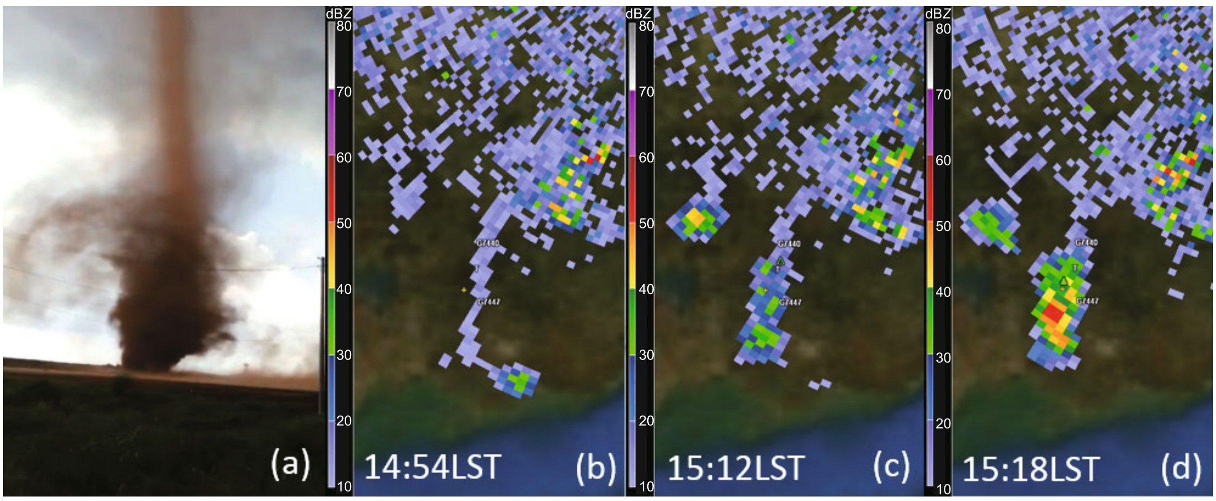

Fig. 7. (a) The debris cloud of the tornado that occurred in Xuwen County, Zhanjiang City, Guangdong Province on 30 July 2016, and (b–d) low-level reflectivity fields from the Zhanjiang operational S-band radar.

with significant wind shift and convergence across the boundary shortly before the tornado. This sea-breeze front did not move much, and a weak reflectivity echo was evident at 1454 LST along the front (Fig. 7b). By 1512 LST (Fig. 7c), the maximum low-level reflectivity reached 40 dBZ and, by 1518 LST (Fig. 7d), 50 dBZ was reached at a location a few kilometers south of the observed tornado site. By 1530 LST, 50 dBZ reflectivity was observed at the tornado location (not shown). The radar and surface station data suggest that the tornado formed along the sea-breeze front underneath a rapidly developing convective storm that, 20 or so minutes later, produced 50+ dBZ reflectivity at the low levels. This appears to be another case of non-supercell tornadogenesis, where a rapidly developing convective storm acts to stretch pre-existing and/or frictionally generated vorticity to cause rapid vortex intensification near the ground. Because of the lack of precipitation before tornadogenesis, baroclinic vorticity generation could not have played an important role. The conceptual model of Wakimoto and Wilson (1989) for non-supercell tornadogenesis appears to apply here, while the conceptual model of Roberts et al. (2016) on the role of surface friction in a rapidly developing tornado may also be applicable. The exact processes as well as the mesoscale environmental conditions for this tornado require further study.

5. Typhoon Mujigae (2015) outer rainband tornado in Shunde, Guangdong Province

In an outer rainband of the landfalling Typhoon Mujigae (2015), a significant tornado was spawned from a mini-

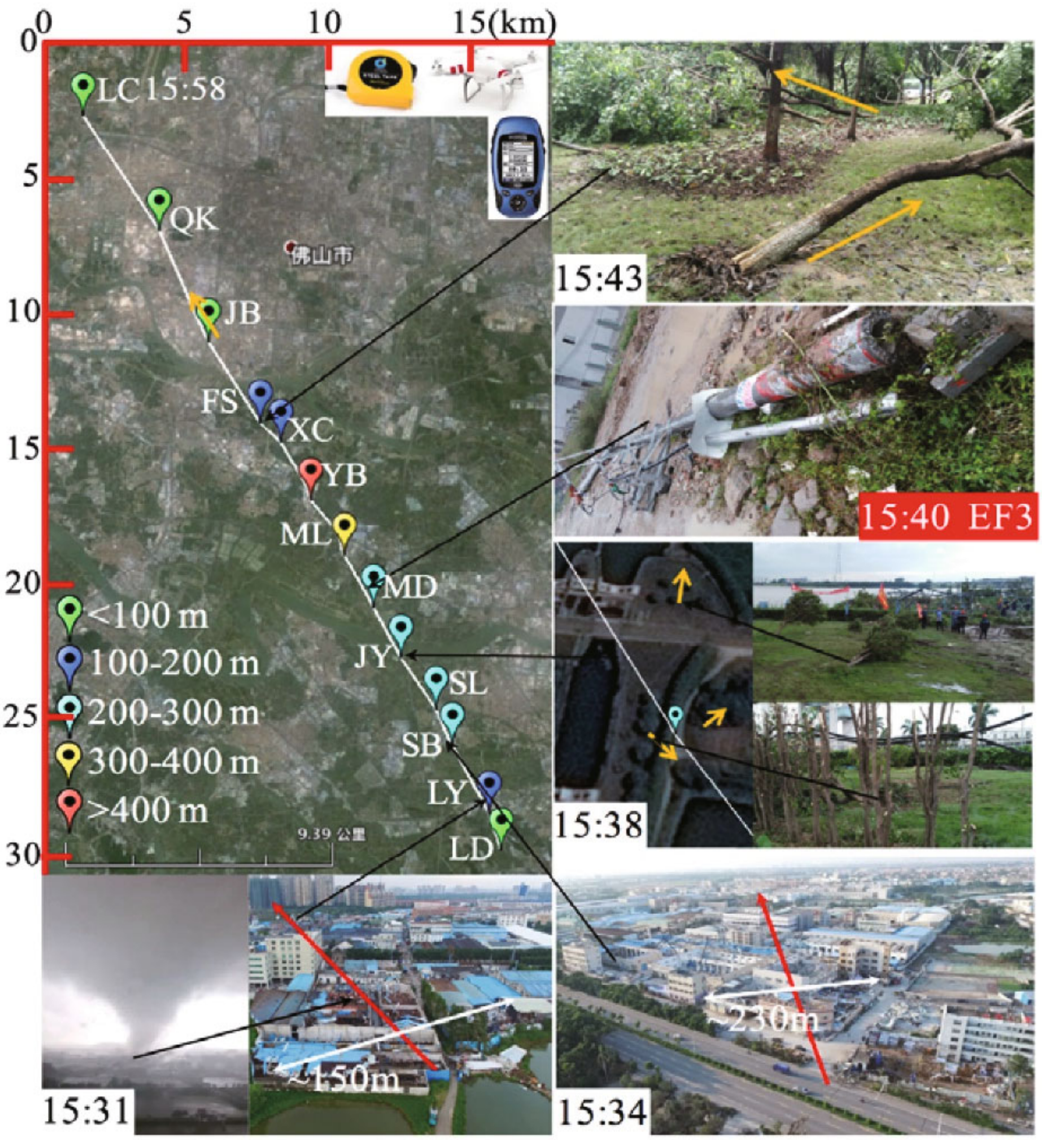

Fig. 8. Damage path, funnel cloud photo, and pictures from the ground damage survey for the tornado that formed in an outer rainband of the landfalling Typhoon Mujigae (2015). The damage path width is also indicated in the damage path figure. Adopted from Zhao et al. (2016).

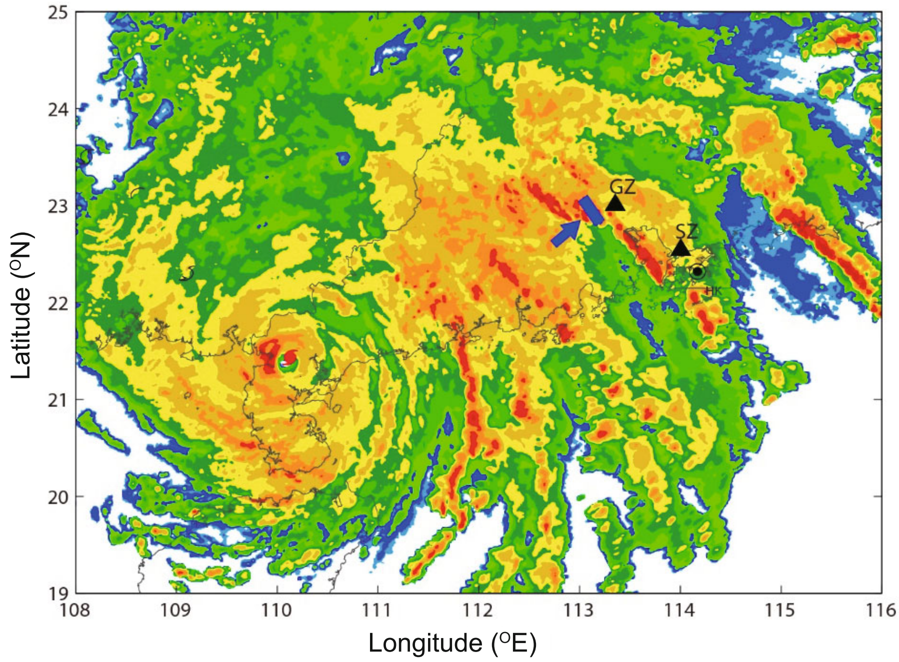

Fig. 9. Composite radar reflectivity covering Typhoon Mujigae (2015) at 1500 LST 4 October 2015. The tornado track is indicated by the thick blue line segment pointed to by the blue arrow.

supercell that passed through Shunde District of Fushan City in the afternoon of 4 October 2015. The tornado formed near 1530 LST (0700 UTC), and lasted for more than 20 minutes. It produced a 30-km long ground damage track, and the track width was 100–500 m (Fig. 8). The tornado was captured on video and in photographs that showed a clear tornado funnel. It was rated EF3 based on damage surveys, caused 4 deaths and up to 80 injuries. The mini-supercell was located east-northeast and about 350 km from the typhoon center (Fig. 9). This tornadic event has been documented in some detail in Zhao et al. (2016). Zhao et al. (2016) showed that the tornado-spawning mini-supercell had the characteristics of those tornadic mini-supercells found in landfalling hurricanes in the United States, and had a small and shallow mesocyclone that lasted for more than two hours. The mesocyclone could be identified from radar data one hour before tornadogenesis, and the maximum intensity of the mesocyclone coincided well with the tornado touchdown time. Vorticity budget analyses were also performed based on dual-Doppler wind retrievals in Zhao et al. (2016), and the tilting of the low-level horizontal vorticity into the vertical and subsequent stretching of vertical vorticity were believed to be the main reasons for the mesocyclone intensification. Additional details on this case can be found in that paper.

6. Concluding remarks

The four tornadoes briefly introduced in this paper occurred in China within 10 months of one another. One was from a heavy precipitation supercell storm, one was from a mini-supercell within a typhoon rainband, and two were non-supercell tornadoes forming along a surface convergence boundary underneath rapidly developing cumulus clouds. Because of the relatively rarity of tornadoes in China, tornado research and forecasting have not been a top priority. Nonetheless, those tornadoes that do occur in China, including EF4 intensity ones, cause increasingly significant damage as the country's economy grows. Research on tornadogenesis dynamics and environmental conditions associated with tornadoes in China is therefore badly needed, and forecasting and warning operations for tornadoes are also clearly necessary. These and other cases with good coverage of observational data provide excellent opportunities for furthering such research and applications.

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REFERENCES

Brooks, H. E., G. W. Carbin, and P. T. Marsh, 2014: Increased variability of tornado occurrence in the United States. *Science*, **346**, 349–352.

Fan, W. and X. Yu, 2015: Characteristics of spatial-temporal distribution of tornadoes in China. *Meteorology*, **41**, 793–805 (in Chinese).

McDonald, J. R., and K. C. Mehta, 2006: A recommendation for an Enhanced Fujita scale (EF-Scale). Wind Science and Engineering Center, Texas Tech University.

Roberts, B., M. Xue, A. D. Schenkman, and I. Daniel T. Dawson, 2016: The role of surface friction in tornadogenesis within an idealized supercell simulation. *J. Atmos. Sci.*, **73**, 3371–3395.

Roberts, R. D., and J. W. Wilson, 1995: The genesis of three non-supercell tornadoes observed with dual-Doppler radar. *Mon. Wea. Rev.*, **123**, 3408–3436.

Wakimoto, R. M., and J. W. Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.*, **117**, 1113–1140.

Zhao, K., M. Wang, M. Xue, P. Fu, Z. Yang, Y. Zhang, W.-C. Lee, F. Zhang, Q. Lin, and Z. Li, 2016: Doppler radar analysis of a tornadic miniature supercell during the Landfall of Typhoon Mujigae (2015) in South China. *Bull. Amer. Meteor. Soc.*, conditionally accepted.

Zheng, Y., W. Zhu, D. Yao, Z. Meng, M. Xue, K. Zhao, Z. Wu, X. Wang, Y. Zheng. 2016: Wind speed scales and rating of tornado in Funing County, Jiangsu Province on 23 June 2016. *Meteorological Monthly*, accepted. (in Chinese)