Science Bulletin 64 (2019) 143–145

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

Importance of identifying tropical cyclone tornadoes in typhoon warning and defense systems

Dan Yao *, Xudong Liang *, Qing Meng, Jian Li, Chong Wu, Zhengshuai Xie, Dandan Chen, Jianping Guo

State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China

Tornadoes are highly localized severe weather phenomena and have been of increasing concern in China [1] in recent years, especially after the sinking of the *Oriental Star* in 2015 [2] and severe tornado damage in Yancheng in 2016 [3]. Tornadoes induced by tropical cyclones, however, have received little attention.

A recent study has shown that a large number of tornado-scale vortices can be produced at the inner edge of the intense eyewall convection of tropical cyclones [4]. This is in agreement with observations of tropical cyclones, both offshore (e.g., Hurricane Katrina in 2005 [5]) and onshore (e.g., Hurricane Ivan in 2004 [6]). Theoretically, tropical cyclones are capable of producing strong low-level vertical wind shear and a low lifting condensation level and therefore may provide an ideal background for the formation of tornadic supercells. The structures associated with tropical cyclones may facilitate the genesis of tornadoes in the rain bands as they make landfall, including dry air intrusion accompanied by a notably higher convective available potential energy [7]. The baroclinic zones generated along the coastline will increase the rotation of the updraft [8]. The damage caused by typhoons or hurricanes may therefore increase to tornado-scale wind damage with the predicted increase in the activity and destructive potential of tropical cyclones in response to global warming [9].

It is extremely difficult to distinguish tornadoes spawned in tropical cyclones (TC-tors) in observational data. The threat of TC-tors did not attract much attention in China until the occurrence of the strong EF3 tornado triggered by Typhoon Mujigae (2015) in Foshan, Guangdong [10,11]. Our knowledge of TC-tors remains limited and the development of improved techniques or instruments to obtain first-hand observational evidence about these destructive weather events is crucially important.

A total of 12 tornadoes were reported in August 2018 at Tianjin, Shandong and Jiangsu in northern China, areas affected by Typhoon Yagi (Fig. 1). Except for the first tornado reported at Jinghai, Tianjin on August 13, which was embedded in a pre-tropical cyclone squall line, most of the tornadoes were spawned in mini-supercells along the tropical cyclone rain band on August 14. A research group equipped with an unmanned aerial vehicle (UAV) from the State Key Laboratory of Severe Weather (LaSW), Chinese Academy of Meteorological Sciences conducted a comprehensive onsite survey of the damage caused by the TC-tors. With the aid of local meteorological bureaus, key sites with damage reports for severe tornadoes were investigated by interviewing victims and witnesses and by verifying videos and photographs of tornado funnel clouds. Although we cannot determine the exact number of tornadoes produced in this outbreak, we verified nine tornadoes in our damage survey (Fig. 1).

Tornadic vortex signatures (TVSs) were identified on radar images for some of the tornadoes and the locations with TVSs coincided with the occurrence of tornado damage (e.g., the images from the radar system installed at Binzhou). By definition, a TVS refers to a significant gate-to-gate tangential wind shear pattern in the radial velocity field on Doppler radar observations [12]. The collocation of the TVSs and verified tornadoes at specific locations provide confidence in establishing an operational system for future tornado warnings.

The most interesting discovery in this survey was the fact that different vortex patterns can be seen at three different scales. The first vortex pattern is at the scale of the tropical cyclone, represented by the tropical cyclone rain band (Fig. 2a). The second vortex pattern is at the storm scale in the convective cells that make up the rain band (Fig. 2b and c). A vortex on this scale is often referred to as a mesocyclone in supercells or a meso-vortex in quasi-linear convective systems (e.g., squall lines and bow echoes). A smaller scale, but more intense, vortex embedded in a mesocyclone is the TVS. At the lowest elevation angle, a TVS often, but not always, indicates the occurrence of a tornado. The TVS is usually larger than the tornado, except for the minority of tornadoes with a wide funnel cloud.

The third vortex pattern is the intense tornado-scale vortex seen near the ground. Three categories of damage swaths left by verified tornadoes can be seen in the damage swath observed with the UAV: type I, a straight damage swath indicating a single, steadily propagating vortex; type II, a zigzag damage swath with clear traces of multiple vortices merging into the main track; and type III, a scattered, hole-shaped damage swath without a clear track.

The first tornado that hit Jinghai, Tianjin provides a good example of a type I damage swath. A continuous track observed by the UAV indicates that the tornado propagated slowly and steadily (Fig. S1a online). A distinct gradient is seen at the edge of the damage swath, with roughly evenly distributed damage inside the swath and unharmed buildings and crops outside. This is

* Corresponding authors.
E-mail addresses: yaod@cma.gov.cn (D. Yao), liangxd@cma.gov.cn (X. Liang).

https://doi.org/10.1016/j.scib.2018.12.022

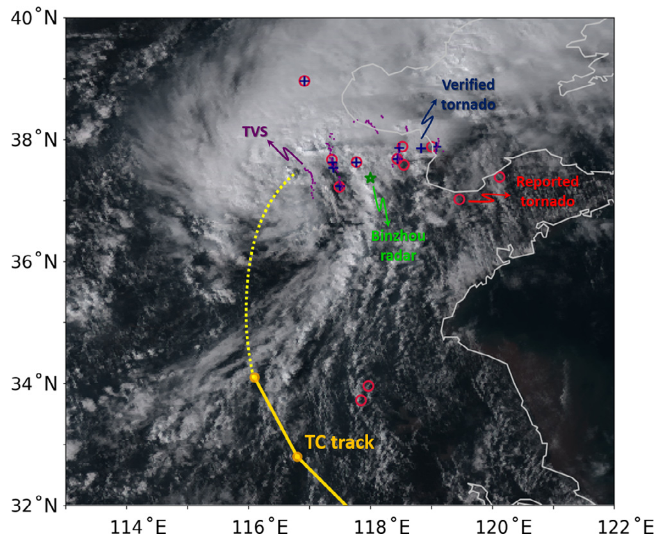

Fig. 1. Locations of tornado reports (red rings), tornadoes verified by LaSW (blue crosses) and TVS analyzed using Binzhou radar observation (violet dots) overlaid with the track of Typhoon Yagi (August 2018) at 1440 LST observed by the Himawari-8 satellite.

consistent with videos of the funnel cloud and descriptions from people affected by the tornado.

The tornado in Huimin, Binzhou is a good example of a type II damage swath. Clear trajectories of small-scale vortices can be observed along the tornado track, merging into the main damage swath (Fig. 2d). This may indicate a tornado with multiple vortices, but the complete three-dimensional structure is still unclear and there are thinner traces left by projectors (e.g., steel roofing sheets; Fig. S1b online).

The tornado in Lijin, Dongying is a good example of a type III damage swath (Fig. S1c online). The scattered hole-shaped damage swath suggests that the tornado was fairly unstable near the ground, probably because it was weaker than the other two types. It touched the ground at certain locations and shrunk upwards in between. This type of trace has not previously been perceived as a tornado track.

The damage swaths obtained from aerial photographs taken by the UAV laid a solid foundation for identifying the underestimated threat of tornado damage exerted by tropical cyclones. This case study strongly suggests that tornadoes may have been neglected by weather forecasters and local governments using the current Doppler radar network. This is especially true for tornadoes occurring at long distances (e.g., >50 km) from the radar station, where the observed height and resolution are limited. The damage swaths

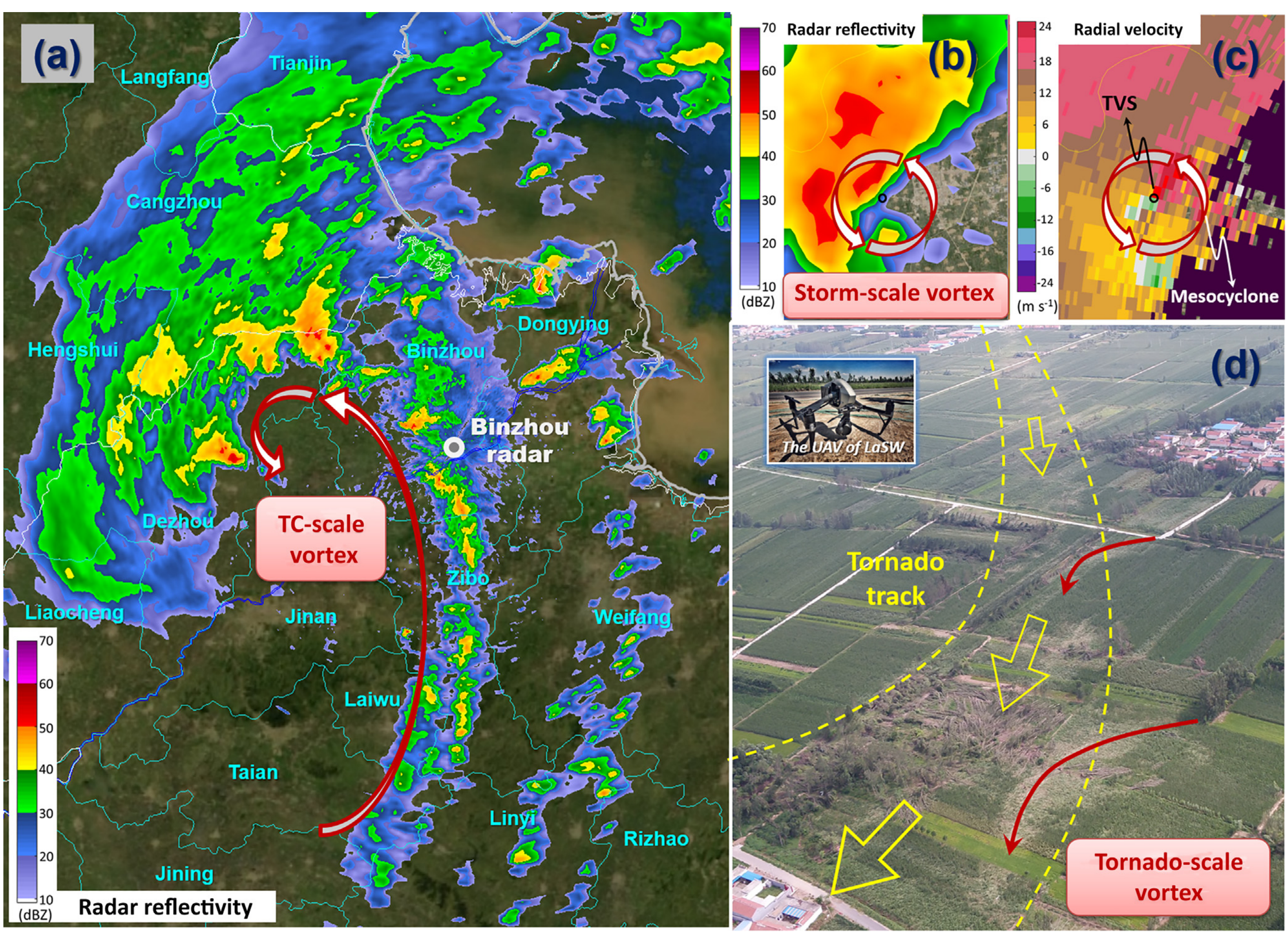

Fig. 2. Multiscale vortex structure from tropical cyclone to tornado. (a) Reflectivity on a 0.5° plan position indicator (PPI) of the tropical cyclone rain band at 1438 LST on August 14, 2018 observed by S-band radar at Binzhou. (b) Reflectivity on a 0.5° PPI of a tornadic supercell at 1251 LST passing Huimin, Binzhou. (c) Radial velocity on a 0.5° PPI of a tornadic supercell at 1251 LST passing Huimin, Binzhou. (d) Damage swath of a tornado embedded in this supercell recorded by the UAV.

seen in aerial photographs obtained by the UAV could be used as a supplementary tool to give a better understanding of the underestimated threat of the tornado damage exerted by tropical cyclones. Social media platforms can be a powerful way to collect information on tornadoes, together with verifications by thorough onsite surveys of the damage. Aerial photographs obtained by UAVs have the potential to provide detailed information on various types of tornadoes on a scale much finer than present day observation techniques.

Tropical cyclones are among the most devastating weather events in China, causing severe flooding and wind damage. The tornadoes associated with tropical cyclones are even more intense in some local regions, but currently receive less concern and are harder to predict or defend against. For now, tornado watches or warning systems are beyond the scope of operational weather forecasting and warning systems in China. Our preliminary findings call for comprehensive investigations by combining state-of-the-art radar observations that can resolve tornadoes with numerical simulation techniques. This will improve our understanding of the genesis of TC-tors and, in the long term, achieve the ultimate goals of accurate prediction, warning and defense against future tornado hazards.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

The authors sincerely appreciate the help from all who have contributed to the onsite tornado damage survey: Zhiyong Meng from Peking University; Lanqiang Bai from Sun Yat-sen University; Xiaoling Zhang, Yongguang Zheng, Wenjian Zhu and Liang Guan from the National Meteorological Center, China Meteorological Administration; Runxiang Gao, Gaohong Dong, Dongmei Meng, Xiaojun Yang, Yinghua Wei, Leilei Zhu, Yajun Du, Cewei Dou and Dongmei Huang from the Tianjin Meteorological Bureau; and Xiaoxiang Zhu, Chengfang Yang, Xiuguang Diao, Xiangui Meng, Zhenhai Li and Shujun Wu from the Shandong Meteorological Bureau. This work was jointly supported by the Ministry of Science and Technology of China (2018YFC1506103), the National Natural Science Foundation of China (41705028), and the Basic Research Fund of the Chinese Academy of Meteorological Sciences (2017Y018).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2018.12.022.

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Dan Yao is an assistant research scientist in the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences. His research interest focused on the damage survey, observation, simulation and dynamics of tornadoes in China. He was a member in the investigation groups for the sunken Oriental Star event on 1 June 2015 and the devastating tornado in Yancheng on 23 June 2016.

Xudong Liang is a senior scientist and the director of the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences. His research interest includes data assimilation, typhoon dynamics and numerical modeling. He has been in charge of leading groups on the development of regional numerical weather prediction systems for East China, North China and East Asia since June 2001.