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• **News & Views** •

Uncertainties in Tornado Records and Potential Solutions from the Perspective of Damage Surveys

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ABSTRACT

Confirming tornado occurrence and estimating tornado intensity are quite challenging, especially for long-track tornadoes and tornado outbreaks, because of the inefficiency or absence of on-site damage surveys, especially in sparsely populated regions, which brings about large uncertainties in the tornado record. Some potential methods to alleviate this uncertainty in tornado records have been introduced, such as reports from tornado enthusiasts, trawling of social media sites, and spaceborne photography, which have been shown to be efficient in collecting damage information and depicting the damage swath and ascertaining tornado records. Unmanned aerial vehicles may help in effectively rating tornado intensities. Since 2021, some of these methods have been being tested or are under operation at the China Meteorological Administration Tornado Key Laboratory and the Foshan Tornado Research Center, and have proved to be effective. They have great potential in advancing tornado or downburst damage surveys nationally or worldwide, as well as assessing tornado climatologies, especially in sparsely populated regions such as Northeast China.

Key words: tornado outbreak, damage survey, unmanned aerial vehicle, spaceborne photography

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1. Uncertainty in tornado records stemming from damage survey

Tornadoes, especially multiple-tornado events, are one of the most destructive natural hazards in China, despite their lower occurrence in contrast to the United States (Fan and Yu, 2015; Xue et al., 2016; Meng et al., 2018; Bai, 2021). Confirming tornado occurrences is still quite challenging. The most direct way to confirm a tornado is by witnessing it. However, in the absence of this, on-site damage surveys along with radar signatures are also effective approaches, such as the tornado vortex signature (TVS) revealed by the radial velocity difference between neighboring pixels, and the tornado debris signature (TDS) revealed by the polarization characteristics of low cross-correlation coefficients (CCs). With the wide use of digital cameras and rapid development of social media, more weak tornadoes are being documented. However, there is still quite large uncertainty in tornado records. Grazulis (2001) showed that only half of all tornadoes have been reported in recent decades in the United States, and half of those that were reported were actually not tornadoes. This large uncertainty is mostly associated with the inefficiency of on-site damage surveys, or the lack of them in sparsely populated regions.

A detailed and effective tornado damage survey comprises the collection of damage information based on degree-of-damage indicators (DIs), such as snapped trees or collapsed houses, and also from interviewing local residents. Tornado damage survey procedures are relatively mature in the United States. To reconstruct a tornado's life cycle, the National Weather Service (NWS) has streamlined the tornado damage survey process to the following steps (Ladue, 2022): (1) determining the initial scope of the tornado event; (2) identifying a survey coordinator to manage survey teams and provide guidance; (3) creating

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a preliminary path to identify where to conduct the on-site survey; (4) contacting local officials to determine the scope of damage and inform them of intentions; (5) identifying single or combined types of ground surveys, aerial surveys, and virtual surveys (based on information from other people's on-site surveys); (6) coordinating with the media to create talking points about the latest survey information; (7) requesting Civil Air Patrol for aerial imagery and/or arranging teams, vehicles, and strategies for ground surveys; (8) analyzing the tornado centerline, tornado perimeter, and tornado rate contours; and (9) disseminating survey results as GIS-based files and storm data. This operational damage survey procedure is facilitated by auxiliary measures such as the official NWS storm spotter network, a post-storm damage survey training course, and the Enhanced Fujita Scale (EF Scale) damage indicator descriptions. For most tornado events, the gathering of information relies on ground surveys; however, some tornado events with multiple casualties and massive DIs may involve aerial surveys using helicopters or unmanned aerial vehicles (UAVs) (Burgess et al., 2014; Wakimoto et al., 2016; Wagner et al., 2019).

There are three main issues with traditional damage surveys that may cause uncertainty in tornado records. The first issue is the lack of damage surveys in sparsely populated regions or deep forest areas. The second issue is the limited time available for collecting DI details in a damage survey. In current practice, videos and photographs are typically manually collected to verify the existence of condensation funnels, estimate the tornado intensity, and confirm the start and end times of the tornado lifecycle. It is a time-consuming task to take photos of all the details of the damage on the ground. Because of the rapid cleanup of DIs by local government agencies right after storms, the time available for damage survey teams is generally quite limited, particularly when multiple tornadoes occur, which may lead to large uncertainties in determining the total number of tornadoes during a single severe weather event. The third issue is the deficiencies in current aerial surveys. Although an aerial survey typically provides a large number of videos and photographs, sometimes it is not sufficient to obtain the details from only a certain direction, and it is hard to provide a complete picture of the damage on the ground. In most cases, it is impossible to conduct quantitative measurements from these photographs. More efficient ways to collect three-dimensional damage information are urgently needed.

2. Methods for effective damage surveys

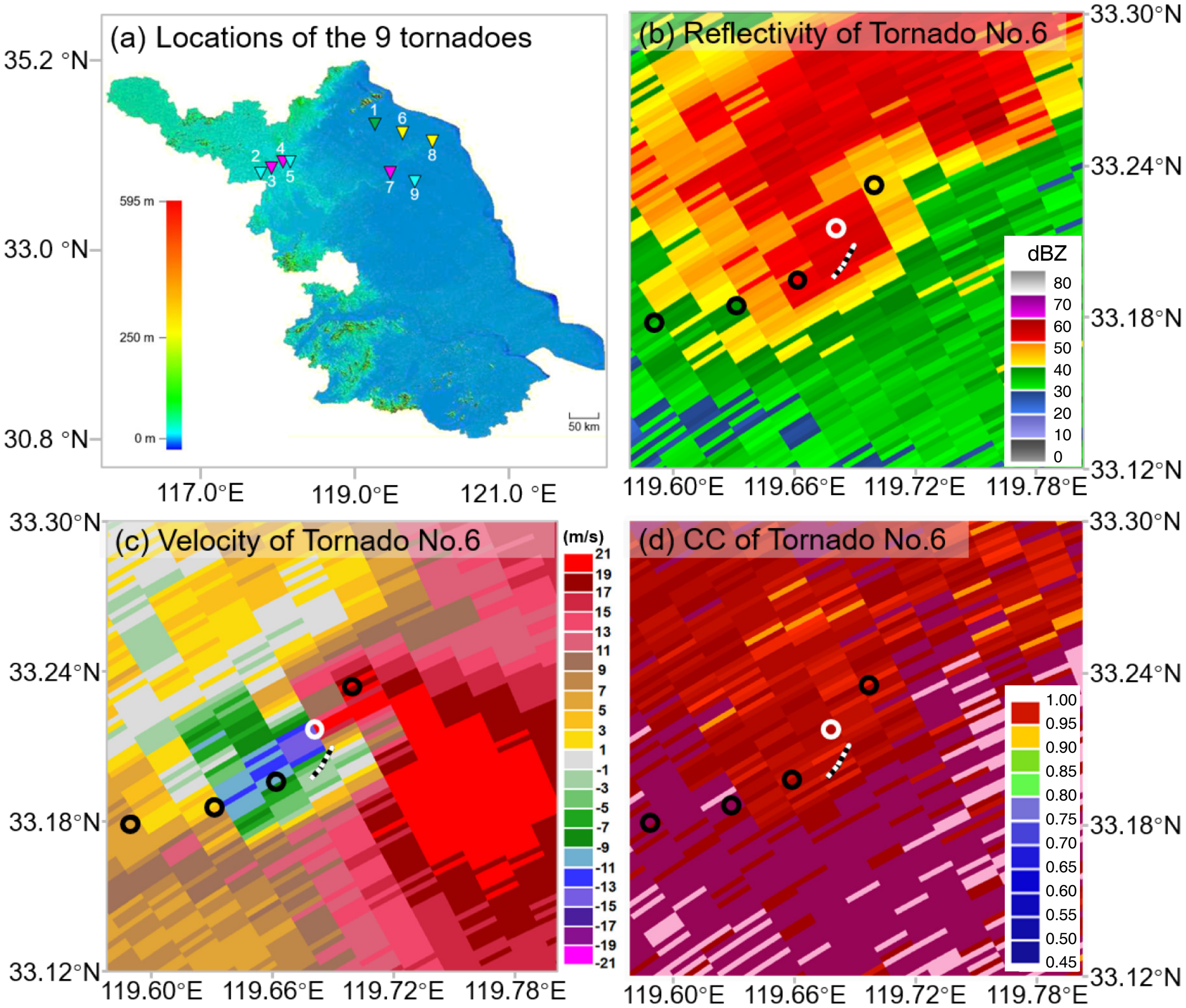
One important way in which the accuracy of tornado counts can be improved is to make efficient use of social media and tornado enthusiasts. Information or videos of tornado events are almost always available during or shortly after a tornado event via social media platforms such as WeChat, Weibo, Bilibili, and TikTok. Such prompt information is extremely helpful in designing damage survey strategies. In 2022, the China Meteorological Administration Tornado Key Laboratory and the Foshan Tornado Research Center developed a social media trawling system that automatically identifies and collects tornado information from websites, and there are plans to improve the system to include video information from Bilibili. In addition, active communication has been established with many tornado enthusiasts who actively and continuously keep an eye on tornado information on social media, which has become another important source of tornado spotting.

One example is the recent high-impact tornadic event on 19 September 2023, during which multiple tornadoes struck the northern part of Jiangsu Province in an environment of an extratropical cyclone (Fig. 1). It was the first recorded tornadic event that occurred in September in Jiangsu (Xu et al., 2021). These tornadoes caused 10 fatalities and tens of injuries, mainly due to the collapse of houses and flying debris. The strongest recorded wind gust from surface weather stations reached 41.8 m s^{-1}.

Immediately after the occurrence of the tornado event, three tornadoes were officially reported by local meteorological agencies (No. 3, 4 and 7 in Figs. 1a and e, indicated by the magenta-colored triangles). On 20 September, an on-site damage survey was conducted by the China Meteorological Administration Tornado Key Laboratory and the Foshan Tornado Research Center, and damage information and tornado videos collected from social media and tornado enthusiasts played a key role.

Damage surveys were performed at nine places where there were either tornado videos or apparent damage. Both ground and ariel surveys were carried out at eight out of the nine places. Only one ground survey was conducted at a single location due to airspace constraints (green triangle in Figs. 1a for Tornado No.1). Information on seven out of nine places of damage was provided by a tornado enthusiast named Zongheng XU, who collected all the tornado information from TikTok, including videos of funnel clouds for tornado No.3 and No. 4, as well as videos or pictures of damage for other tornadoes.

Based on the damage survey, tornadoes No. 2, No. 5 and No. 9 (cyan triangles in Figs. 1a) were confirmed right away on site. Tornadoes No. 1, No. 6 and No. 8 (green and yellow triangles in Figs. 1a) were confirmed after the on-site survey due to time limitations in the situation of multiple tornadoes by manually analyzing the lowest-level radar signatures such as the hook echo, TVS, and TDS along with their spatiotemporal collocations with the damage on the ground collected from the damage survey (e.g., Figs. 1b–d for Tornado No. 6). One place was confirmed as "non-tornado" without a TVS signature. Thus, an additional six tornadoes were added to the three officially reported, and a total of nine tornadoes were ultimately confirmed (Figs. 1a and e), including two EF3, an EF2, five EF1, and an EF0. This case suggests the potential uncertainty



(e) Tornado details obtained from damage surveys

Tornado (No.)	City	County	Time (LST)	Intensity	Longitude (°E)	Latitude (°N)	Length (km)	Strength (m/s)
1	Lianyungang	Guanyun	15:40	EF1	119.195	34.380		28
2	Xuzhou	Suining	16:41	EF1	118.112	33.761	8.3	32.5
3	Suqian	Sucheng	17:11	EF3	118.320	33.839	3.0	23
4	Suqian	Suyu	17:34	EF2	118.503	33.904	14.0	49.5
5	Suqian	Siyang	18:04	EF1	118.606	33.906	2.1	27
6	Yancheng	Xiangshui	18:50	EF0	119.685	34.225	1.1	36.5
7	Yancheng	Funing	20:04	EF3	119.486	33.695	19.0	49
8	Yancheng	Binghai	20:35	EF1	120.199	34.130	0.5	23.5
9	Yancheng	Jianghu	21:31	EF1	119.804	33.635	2.3	46

Fig. 1. (a) Locations of the nine tornadoes confirmed by damage surveys on 19 September 2023 in Jiangsu, China. The magenta triangles denote tornadoes that were officially reported by local meteorological agencies. The cyan triangles denote the tornadoes that were identified by an on-site damage survey. The yellow triangles represent the tornadoes that were determined by manually analyzing the lowest-level TVSs and the storm morphology, such as hook echo signatures on radar products, along with their spatiotemporal collocations with the damage on the ground. The green triangle depicts the tornado based on superposition of the TVS and hook echo signatures and the damage on the ground. Panels (b), (c) and (d) present the reflectivity, radial velocity and CC for tornado No. 6 at 1850 LST, with the TVS shown as the white circle. Other TVSs identified from 1832 to 1856 LST are also given, as black circles. The black-and-white dotted line denotes the center of the disaster area obtained through the damage survey. The table in (e) presents the details of the nine tornadoes including their intensity, length, and strength (maximum gate-to-gate azimuth radial velocity difference).

in tornado counts from single information sources.

As another example, during the tornado event in Liaoning on 1 June 2023, two of the total five tornadoes were confirmed through verifying videos of the condensation funnels from social media and tornado enthusiasts. These two tornadoes occurred in the fields of sparsely populated regions in the counties of Faku and Kangping. Neither the damage on the ground nor the radar products demonstrated distinct tornado signatures. Thus, these two tornadoes might have been missed if it were not for videos from social media.

Concerning the issue of the lack of traditional damage surveys in sparsely populated regions or deep forest areas, spaceborne photography is an alternative and effective method to depict the damage swath. Previous studies have shown that satellite remote sensing can provide a complementary way for tornado damage surveys and track detections to be carried out. Yuan et al. (2002) used high-resolution images (23.5 m) from the Linear Imaging Self-Scanning III (LISS-3) sensor to evaluate damage characteristics for the tornado outbreak event on 3 May 1999 in Oklahoma. They compared three methods to distinguish different tornado scales. Based on the satellite images, surface weather station observations and reanalysis data, Shikhov and Chernokulsky (2018) demonstrated that 105 out of 110 tornado tracks identified from 2000 to 2014 in the forests of northeastern Europe were discovered for the first time, which offered valuable information for assessing tornado climatologies in sparsely populated or forest regions. Spaceborne photography may become an important way to assess tornado climatologies in sparsely populated Northeast China. As demonstrated in Fig. 2a, satellite images show an obvious track and an affected area of a tornado on 8 September 2021 in the forest of Liaoning, China. Furthermore, another narrow and elongated damage swath in a sparsely populated region was also demonstrated in Liaoning in Landsat satellite images for the Kaiyuan tornado on 1 June 2023 (Fig. 2b).

Another method that may improve conventional damage surveys is the user-friendly method of UAVs, which could prove very useful for rating tornadoes in damage surveys because of their rapid capability, wide detection ranges, and automated image acquisition (Rolly et al., 2022; Laghari et al., 2023). UAVs are becoming smaller in size, which is making it easier to carry out damage surveys. A three-dimensional (3D) model of UAV tilt photogrammetry technology incorporates hardware of a multi-rotor UAV equipping with a micro-tilt camera platform and five lenses, and software of precise positioning system and agile modeling. The tornado affected area can be rapidly identified and 3D damage images can be rapidly obtained from the software by taking omnidirectional multi-view stereo (MVS) images of the surroundings (Guo et al., 2022). With the five-lens equipment on the UAV, an MVS image of the surroundings was taken (Fig. 3a). This image was then processed digitally for a better structure of plane and elevation with proper color and texture (Figs. 3b and c). The 3D damage image was then reconstructed according to unified coordinates (Fig. 3d).

The 3D modeling of UAV tilt photogrammetry technology has been under testing at the China Meteorological Administration Tornado Key Laboratory and the Foshan Tornado Research Center. Since 2021, damage information of 14 tornadoes have been reconstructed using this technology shortly after automated image acquisition. The size of the affected area and even the diameter of snapped trees can be accurately measured, which greatly boosts the efficiency of the damage survey.

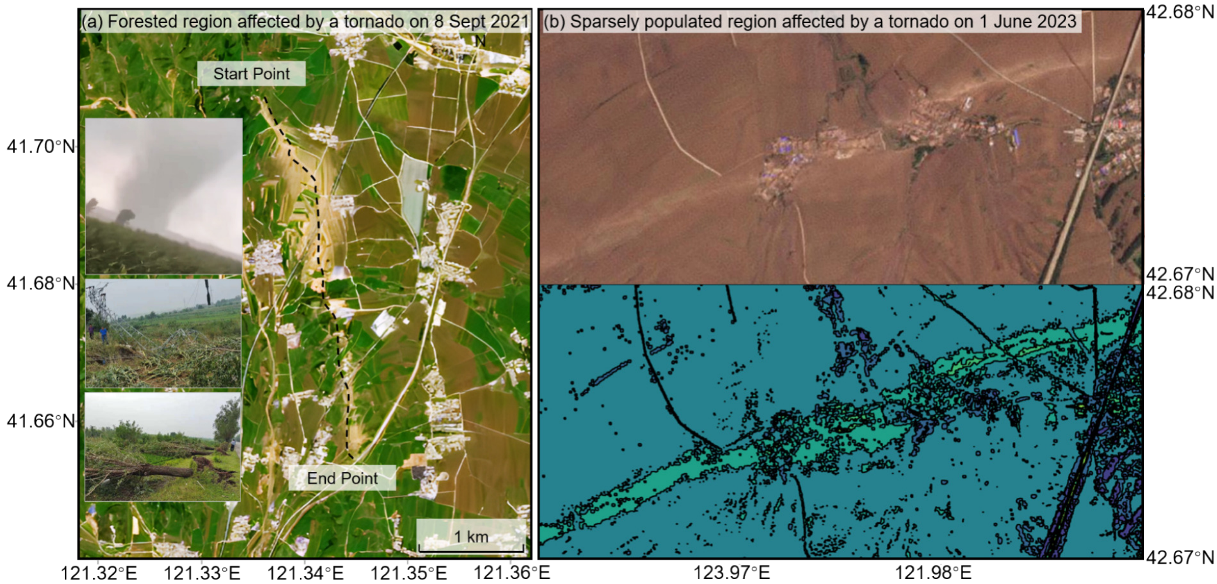


Fig. 2. (a) The track of a tornado determined by satellite imagery in the forested region of Liaoning, China, on 8 September 2021. (b) Narrow and elongated affected area of the Kaiyuan tornado demonstrated by spaceborne photography in the sparsely populated region of Liaoning, China, on 1 June 2023.

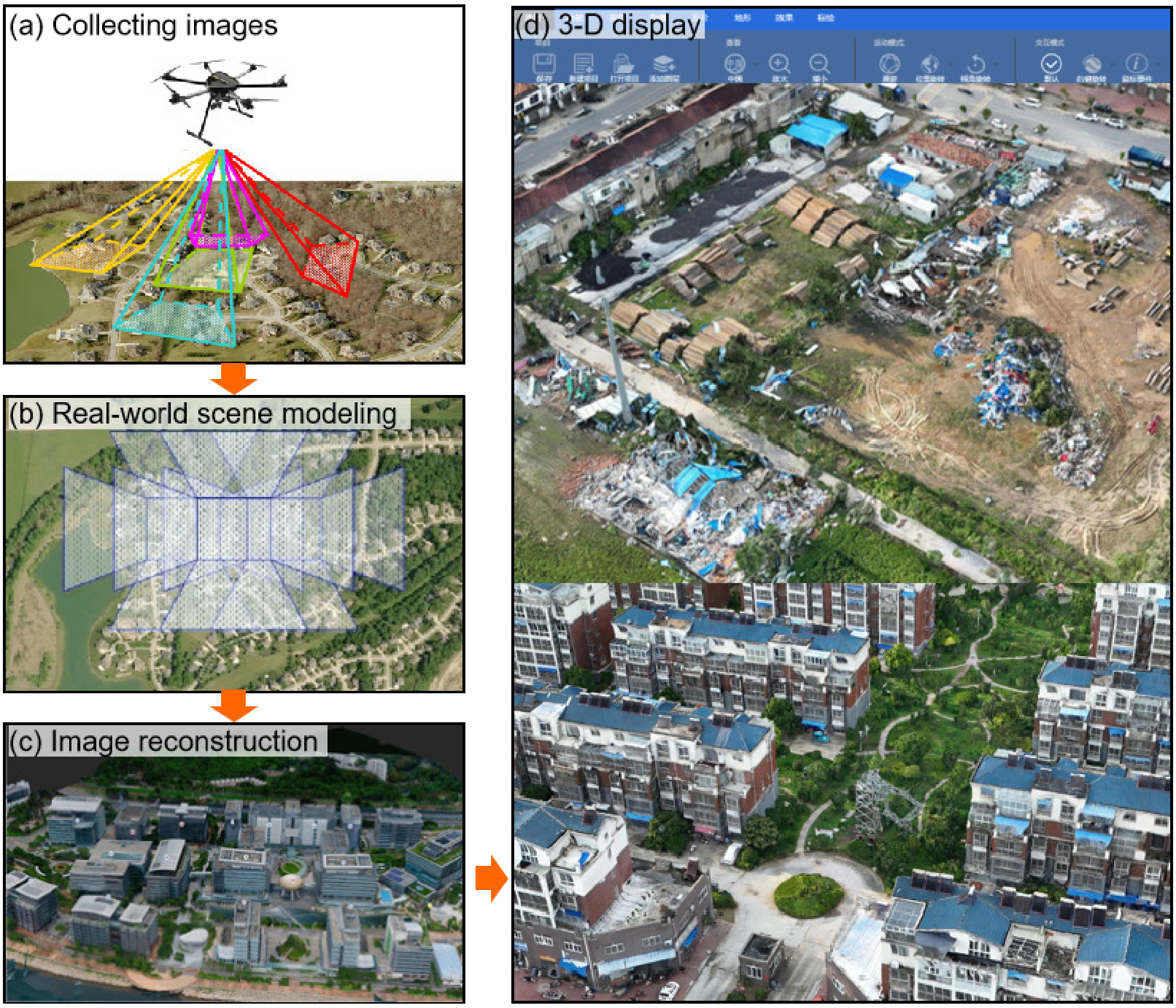


Fig. 3. Schematics of 3D modeling of UAV tilt photogrammetry technology for tornado No. 3 of the multiple-tornado event as shown in Fig. 1a.

In the high-impact tornadic event on 19 September 2023 in Jiangsu Province, China, this technique was used for one of the nine tornadoes (No. 3 in Fig. 1a and Fig. 3).

Any tornado damage survey method will inevitably contain some uncertainties. For the 3D modeling of UAV tilt photogrammetry technology, it is highly efficient for measuring the size of the affected area and even the diameter of snapped trees, but its application is forbidden in no-fly areas such as in the vicinity of airports, and cannot work in conditions of strong winds and precipitation. Spaceborne photography is less affected by strong winds, but it is difficult to use it to detect weak tornadoes leaving indistinct marks, such as the weak tornado that happened on 12 April 2024 in Tongliao of Inner Mongolia Autonomous Region. Information on tornado events is broadcast rapidly via social media platforms, such as Bilibili and TikTok, during or shortly after the event, but it can sometimes be hard to find the original video with an exact record of the time of tornado touchdown. Meanwhile, information and videos from websites need to be verified to avoid fake ones.

With fast progress in information techniques and social media, although there are some shortcomings for these different tornado survey methods, the uncertainties in the tornado record around the globe are expected to be greatly reduced through the efficient use of timely information from social media platforms, 3D modeling of UAV tilt photogrammetry technology, and spaceborne photography.

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