Environmental Conditions, Evolution and Mechanisms of the EF4 Tornado in Kaiyuan of Liaoning Province of China on 3 July 2019

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Yongguang ZHENG, Yu LAN, Yancha CAO, et al., 2020: Environmental conditions, evolution and mechanisms of the EF4 tornado in Kaiyuan of Liaoning Province on 3 July 2019.Meteor. Mon.,46(5), 589-602 (In Chinese).

1.INTRODUCTION

On the afternoon of 3 July, 2019, during 17:17-17:47 (Beijing time, the same below), some areas in Kaiyuan City of Tieling City of Liaoning Province of China experienced rare severe convective weather of an EF4 tornado, hail, and short-time heavy precipitation. The length of the EF4 tornado's path was about 14 kilometers, causing a total of 7 deaths, more than 190 injuries, and serious economic losses (Figure 1).

This study comprehensively applies the NCEP (National Center for Environmental Prediction of the United States of America) CFSR (Climate Prediction System Reanalysis) 0.5° × 0.5° reanalysis data and multi-source high-spatial-and-temporal-resolution observation data such as radiosonde, automatic weather stations, Shenyang wind profiler, FY-4A multi-channel images and lightning imager (LMI), China National Lightning Monitoring and Positioning Network (NLLN) [observation of cloud ground lightning (referred to as ground lightning)], Shenyang and Liaoyuan new generation weather radar, a detailed analysis of the EF4 tornado process in Kaiyuan will be conducted to further enhance our understanding of the environmental conditions, characteristics, and physical mechanisms of tornado formation and dissipation.

2.SEVERE CONVECTIVE WEATHER

Based on radar and other observation data, as well as the damage survey of the tornado, it has been determined that the maximum intensity of the tornado that occurred in Kaiyuan on 3 July, 2019 during 17:17-17:47 pm reached the EF4 level (Figure 1a and b). According to the observation data (Figure 1c), during 17:00-18:00 on 3 July, the National Meteorological Station of Kaiyuan City only observed a maximum instantaneous wind speed of 23 m/s at 17:46, which was far less than the low limit of the EF4 wind speed range determined by the damage survey, which is 74 m/s. The maximum 1-hour rainfall was 25 mm, and NLLN detected a small amount of ground flash (Figure 1c), which was significantly different from the EF4 tornado process in Funing of Jiangsu Province in 2016.However, the lightning observed by FY-4A LMI appeared more active due to the presence of cloud-to-ground or intercloud flashes (Figure 1c). In addition, hail occurred near the urban area of Kaiyuan. Although meteorological stations did not record it, the maximum hail diameter identified based on radar data could reach 5 cm.

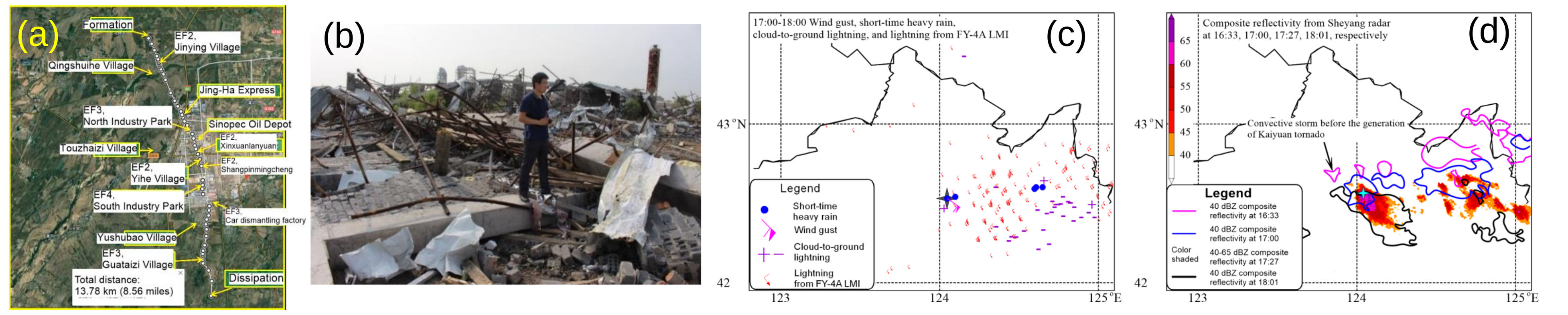

Figure 1 Tornado damage and weather observations
(a) Path and intensity of the Kaiyuan tornado (Yellow solid line marked G1 indicates Beijing-Harbin expressway, adapted from Zhang et al, 2020), (b) a photograph of a canteen in southern area of Kaiyuan Industrial Park taken in the damage survey, (c) high wind, cloud-to-ground lightning, hourly rainfall ≥ 20 mm, and lightning from FY-4A LMI, (d) composite reflectivity from Shenyang radar (In Figures. c and d, star symbol denotes the location of Kaiyuan meteorological station)

3. SYNOPTIC SITUATION AND ENVIROMENTAL CONDITIONS

On 3 July, central northern Liaoning and central eastern Jilin were all affected by the 500-hPa Northeast China Cold Vortex (Figure 2a). The warm and humid conditions in the lower atmosphere on the south side of the cold vortex were very favorable for the occurrence and development of severe convective weather. Research has shown that most Northeast China tornadoes in history occurred in the subsynoptic scale short wave trough on the southern side of cold vortex.

The environmental conditions of this Kaiyuan tornado meet the conditions of large CAPE value and strong 0 – 6 km vertical wind shear, which are conducive to the supercell, as well as the conditions of small CIN and strong 0 – 1 km vertical wind shear, which are conducive to the strong tornado. Therefore, the overall environmental conditions on 3 July were conducive to the occurrence of supercell storms. However, the enhancement of 0 – 1 km vertical wind shear had certain mesoscale characteristics, which was only presented in the radial velocity and wind profile observed by radar. There was a dry layer in the middle and lower troposphere near Kaiyuan on 3 July. The DCAPE was large, and the height of the zero degree layer was about 3.6 km, which is conducive to the occurrence of strong downdraft and strong cold pool and unfavorable to the occurrence of tornadoes. The lower relative humidity in the lower atmosphere and the higher height of uplift condensation (although the CIN value very small) were also unfavorable for the occurrence of the tornado.

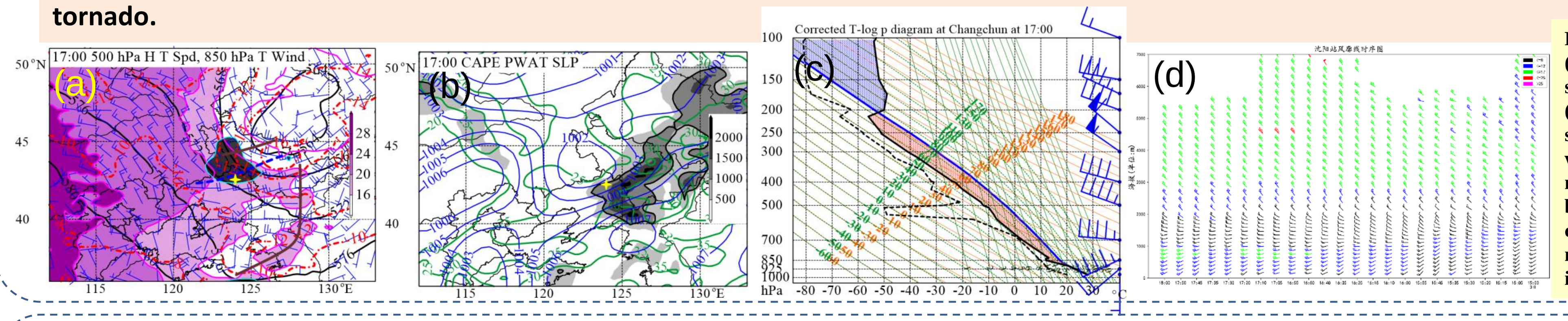

Figure 2 Synoptic situation and environmental conditions for 17:00 BT on 3 July, 2019
(a) Synoptic situation, (b) environmental conditions, (c) modified 08:00 BT t-log p diagram at Changchun using 17:00 BT surface observations at Kaiyuan, (d) time-height wind profiles from Shenyang wind profiler
(Figures a and b are based on CFSR data, and yellow star symbol denotes Kaiyuan meteorological station. In Figure a, black solid lines are 500-hPa geopotential height contours with 4-dgpm interval in dgpm; red dashed lines are 500-hPa isotherms with 2-°C interval in °C; gray colored areas with cyan lines indicate ≥ 20 m/s wind speeds at 500 hPa; color shaded areas with magenta lines are 850-hPa isotherm in °C; blue barbs are 850-hPa winds with full barb of 4 m/s and half barb of 2 m/s; thick blue dashed line represents 850-hPa shear line and thick deep-red solid line denotes 500-hPa trough. In Figure b, blue contours are for sea level pressure at 1-hPa intervals in hPa, green contours are for precipitable water at 5-mm intervals in mm, and gray colors are for CAPE at 500-J/kg intervals in J/kg with thick solid lines of 1000 J/kg. In Figure c, black solid line is temperature curve, black dashed line is dewpoint curve, blue solid line is status curve, and red filled area is CAPE.)

4. CONVECTION TRIGGERING, CONVECTIVE CLOUDS, AND LIGHTNING

At 16:00 (Figure 3a), the surface convergence line, also known as the dry line, entered northern Liaoning. Compared with that of 08:00, the surface dew point on the north side of the convergence line significantly decreased, while the dew point on the south side increased. The humidity gradient on both sides of the dry line significantly increased, while the temperature gradient almost disappeared. At the same time, the linear convective system located in Jilin was moving southward and approaching the northern region of Liaoning, forming a gust front convergence line between its surface outflow airflow and the southwest warm and humid airflow. In the area near the border between northern Liaoning and Jilin, two convergence lines collided, forming a vortex circulation of surface winds such as northeast wind, northwest wind, southwest wind, and southeast wind. Especially, the northwest wind was significantly enhanced compared to that of 15:00, with a maximum wind speed of around 6 m/s, and the southwest wind was also enhanced, with a maximum wind speed of around 8-10 m/s. As a result, surface convergence was significantly strengthened. In addition, CFSR data show an increase in CAPE values (not shown in the figure), therefore, the development of cumulus clouds near the dry line significantly strengthened (as shown in the yellow elliptical area in Figure 3a). The enhanced visible satellite image shows that the texture of these cumulus cloud tops was already very rough, with an infrared brightness temperature of around -19 ℃ (not shown in the figure) and continuously decreasing, indicating that the updraft was developing. The reflectivity observed by Shenyang radar exceeded 35 dBZ (not shown in the figure), forming initiated convection, which eventually developed into a supercell storm leading to the Kaiyuan tornado.

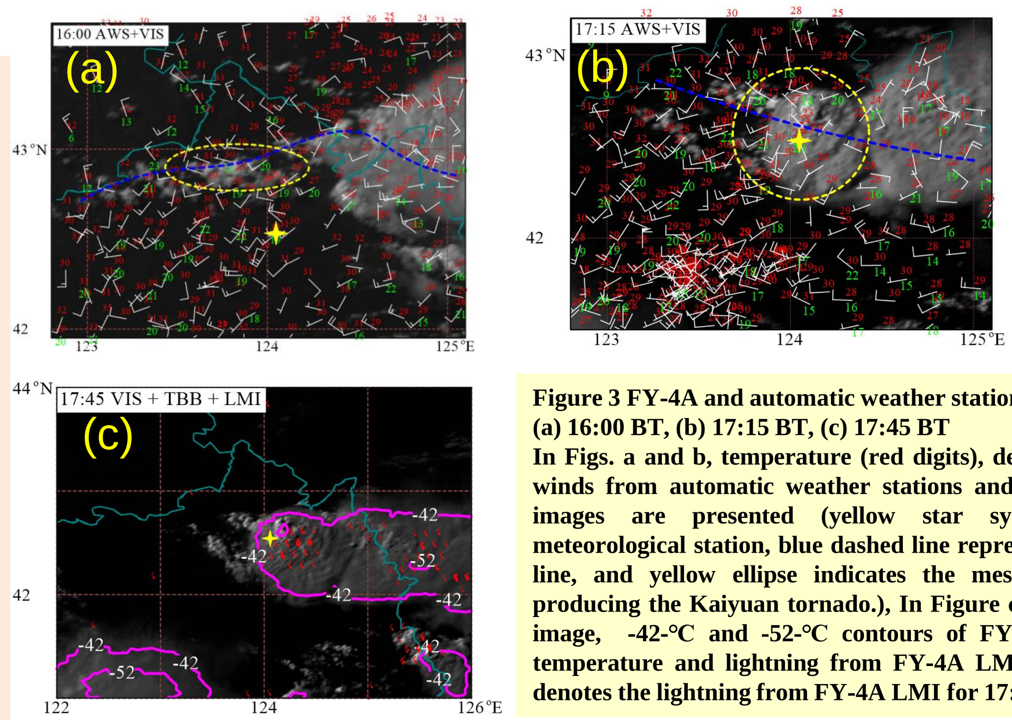

Figure 3 FY-4A and automatic weather station observations for 3 July
(a) 16:00 BT, (b) 17:15 BT, (c) 17:45 BT
In Figs. a and b, temperature (red digits), dewpoint (green digits) and winds from automatic weather stations and FY-4A enhanced visible images are presented (yellow star symbol denotes Kaiyuan meteorological station, blue dashed line represents surface convergence line, and yellow ellipse indicates the mesoscale convective system producing the Kaiyuan tornado.), In Figure c, FY-4A enhanced visible image, -42-°C and -52-°C contours of FY-4A infrared black body temperature and lightning from FY-4A LMI are given (red symbols denotes the lightning from FY-4A LMI for 17:41-17:50 BT).

5.EVOLUTION AND MECHANISM

5.1 EVOLUTION AND STRUCTURE OF CONVECTIVE STORM

As mentioned above, at 16:00, cumulus clouds in the area north of Kaiyuan developed into initiated convection. At 16:33, the convection in the region developed into three convective storms, among which the westernmost convective storm later generated this intense tornado (Figure 1d). By 17:06, the convective storm located in the west of Kaiyuan urban area developed rapidly and strengthened. The maximum reflectivity of Shenyang radar was more than 60 dBZ. The radial velocity field at low elevations had mesocyclone characteristics (not shown in the figure). At this time, it had developed into a supercell, but the tornado had not yet formed (Zhang et al., 2020). Afterwards, it moved from northwest to southeast and affected the urban area of Kaiyuan.

During 17:17-17:44, the mesocyclone of the Kaiyuan tornado detected by the Shenyang radar at elevations of 0.5° and 1.5° developed with some variation in intensity. Taking 17:22 as an example, the cyclone with a rotation speed of at least 24 m/s (positive velocity of 30.5 m/s and negative velocity of 18 m/s) at 0.5° elevation (Figure 4c), and with a rotation speed of 30.5 m/s (positive velocity of 30 m/s and negative velocity of 31 m/s) at 1.5° elevation (Figure 4d) belonging to a strong mesocyclone. The mesocyclone simultaneously exhibited a tilt towards the mid-troposphere downwind direction (i.e. southeast direction), resulting in a tilted hook echo (as shown in the blue and red box positions in Figure 4d). The tornado occurred below the mesocyclone at 0.5° elevation of the Shenyang radar, near the hook echo, which was located near the interface between the rear downdraft and the front flank updraft (red dots as shown in Figures 4c and d). Figures 4c and d indicate that the convective storm also exhibited a significant TVS characteristic.

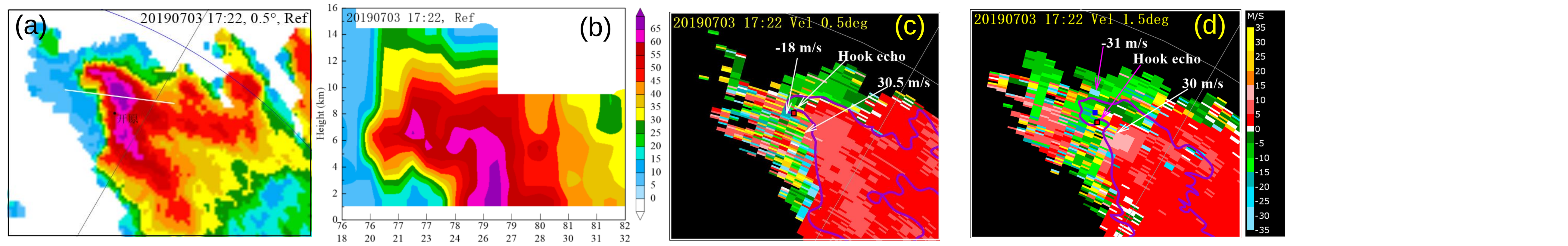

Figure 4 Shenyang radar observations at 17:22 BT on 3 July
(a) and (b) are for reflectivity at 0.5° elevation and in vertical cross section, respectively; (c) and (d) are for radial velocity (color shaded) with 40-dBZ reflectivity contour (purple thick solid line) at 0.5° and 1.5° elevations, respectively (In Figure b, the top digits below the abscissa are distances from Shenyang radar station in km; and the bottom digits are azimuth angles in ° with north of 0° and clockwise increase; altitudes are on the left side of the ordinate in km. In Figure d, blue square symbol represents the location of hook echo at 0.5° elevation)

5.2 COLD POOL AND TORNADO FORMATION AND DISSIPATION MECHANISM

During17:15-17:45, the temperatures at automatic weather stations show that the downdraft of the tornadic convective storm caused obvious temperature drop at the surface, forming an obvious cold pool. At 17:15, when the tornado was approaching its formation (Figure 5a), the surface temperature of the cold pool was about 23-27 ℃, and the surrounding environment temperature was about 29-30 ℃. The temperature difference between the two was about 2-7 ℃. It should be noted that, at the position where tornado was generated near the hook echo, although the distribution of automatic weather station was relatively sparse, it can still be found that the temperature difference there was obviously small, about 2-4 ℃. Therefore, as mentioned earlier, this small temperature difference provided a physical mechanism for the strengthening of vertical vorticity near the ground for the formation of this tornado, which was conducive to the formation of the tornado.

However, the unfavorable environmental conditions for the formation of this tornado were low relative humidity in the lower troposphere, which is conducive to the generation of strong cold pools and not conducive to the generation of weak cold pools (Doswell and Evans, 2003). So, what is the reason for the weaker cold pool and smaller temperature difference at this time? From the morphology and evolution of the convective storm shown in Figures 1d and 4, it can be seen that the long axis of the convective storm was in the north-south or northwest southeast direction and moved southward, while the tornado generated near the hook echo in the northwest of the convective storm. Therefore, before the tornado generated, precipitation already occurred in the front of the convective storm in Kaiyuan and surrounding areas, and automatic weather stations indeed observed precipitation (not shown in the figure). As a result, the atmosphere in this area was rapidly saturated and the relative humidity was significantly increased, and the rear inflow of the convective storm was relatively weak compared with that of the tornado in the dissipation period, so that the intensity of the cold pool caused by the downdraft would not be too strong and be appropriate when the rear part of the convective storm moved to the area where the tornado occurred. In addition, the boundary layer of the tornado at this time had strong warm moisture inflow, strong vertical wind shear in the lower and middle layers, and very strong updraft, as shown in the above analysis. Therefore, the combined effect of these factors as above determined the formation of the tornado.

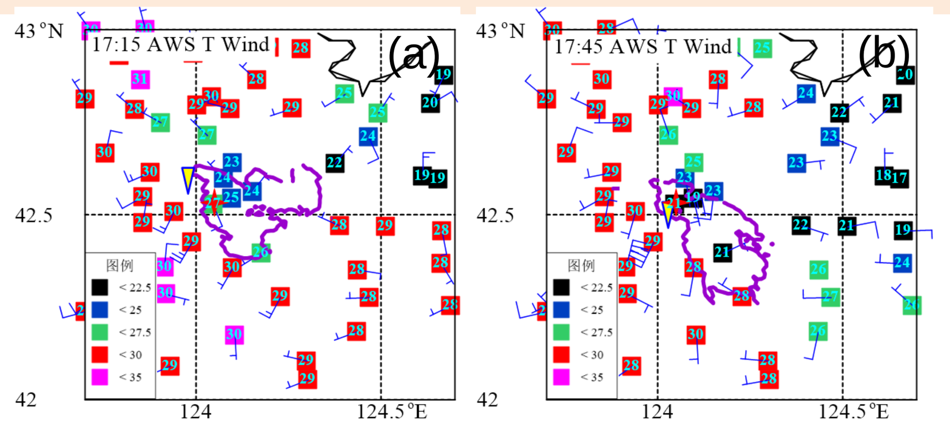

Figure 5 Temperatures and winds from automatic weather stations for 3 July
(Rectangles with different colors marked digits indicate temperatures. Red star symbol denotes the location of Kaiyuan meteorological station, yellow inverted triangle represents the location of hook echo at 0.5° elevation, and purple thick solid line is the 40-dBZ reflectivity contour at 0.5° elevation of the tornadic supercell from Shenyang radar.)
(a) 17:15 BT, (b) 17:45 BT

6. CONCLUSIONS

At around 16:00 on 3 July, the strengthened dry line met the gust front in the southward convective system, triggering the convective storm that caused the Kaiyuan tornado.

The mechanism of the formation and dissipation of the tornado is summarized as follows: under the environment of large CAPE and strong vertical wind shear in the middle layer, the westmost convective storm triggered by the dry line and the gust front formed a supercell, and the downdraft of the storm made the low-level mesocyclone develop and further strengthened the updraft. Before the tornado formation, the front of the convective storm produced precipitation in the tornado formation area to make the atmosphere rapidly saturated. When the rear of the convective storm moved to the area, it was conducive to the formation of a suitable cold pool for its less strong downdraft and the formation of baroclinic vorticity. At the same time, under the combined effect of strong warm moisture inflow in the boundary layer, strong vertical wind shear in the lower and middle layers, and very strong updraft, this convective storm produced the Kaiyuan tornado. With the development of the convective storm, at around 17:45, the strong downdraft formed a strong cold pool, and the significant increase in negative buoyancy suppressed the maintenance of strong vertical vorticity near the surface, leading to the dissipation of the tornado.

Acknowlegement: This work was supported by the National Key R&D Program of China (Grant Nos. 2022YFC3004104, 2018YFC1507504 and 2017YFC1502003) and National Natural Science Foundation of China (Grant No. 41375051)