Environmental Conditions, Evolution and Mechanisms of the EF4 Tornado

Poster #91 ***in Kaiyuan of Liaoning Province of China on 3 July 2019***

Yongguang ZHENG*, Yu LAN, Yancha CAO, Xiaoling ZHANG
National Meteorological Centre, Beijing 100081, China

1. INTRODUCTION

On the afternoon of 3 July, 2019, during 17:17−17:47 (Beijing time, the same below), some areas in Kaiyuan City, Tieling City, Liaoning Province, 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 station, 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,

* *Corresponding author address:* Yongguang Zheng, Univ. of Missouri, National Meteorological Centre, Beijing 100081, China; e-mail: zhengyg@cma.gov.cn.

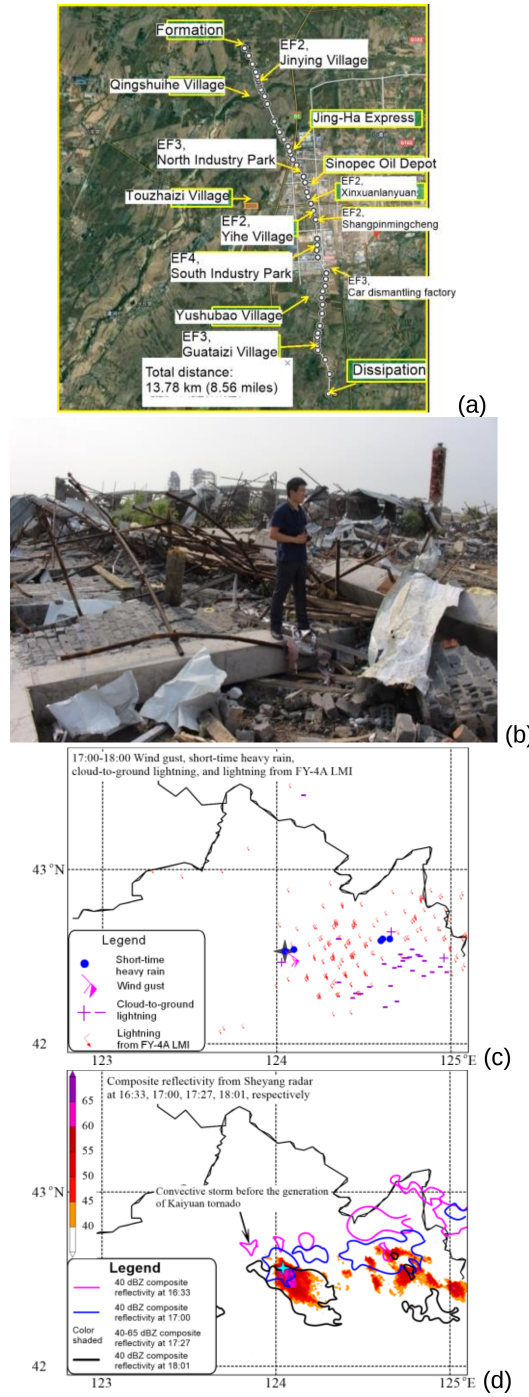


Figure 1 Tornado damage and weather observations (a) Path and intensity of the Kaiyuan tornado (Yellow solid line marked G1 indicates Beijing-Harbin expressway, adapted from Zhang et al, 2020), (b) a photograph of a canteen in southern area of Kaiyuan

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)

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.

The convective weather monitoring in Kaiyuan and its surrounding areas (Figure 1c and d) shows that the convective weather in this area was severe and the spatial distribution scale was small. Radar data (Figure 1d) and FY-4A satellite visible images (see below) show that the convective system that produced the tornado was a relatively isolated supercell, which moved roughly from northwest to southeast by south. The horizontal scale of mature convective storm was about 50-60 km, and the maximum reflectivity exceeded 65 dBZ.

3. CIRCULATION BACKGROUND AND ENVIRONMENTAL CONDITIONS

3.1 SYNOPTIC SITUATION

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 (Wang et al., 2015).

The CFSR analysis data show (Figure 2a) that the Kaiyuan tornado occurred behind the large-scale trough at the southwest side of the 500 hPa cold vortex and in the large gradient area of geopotential height at 17:00 on 3rd July, which was a large-scale subsidence movement area, but in front of the short wave transverse trough, and was located on the right front side of a jet stream with a wind speed of ≥ 30 m/s at 300 hPa and ≥ 20 m/s at 500 hPa. The tornado was located on the right side of the atmospheric temperature gradient zone at 500 hPa, but the temperature advection was not significant. The temperature was about -11 ℃ at 500 hPa, which was significantly lower than the corresponding temperature of about -3 ℃ during the Funing tornado event in 2016. The weather situation at 700 hPa was similar to that at 500 hPa.

When the Kaiyuan tornado occurred, there was a high wind speed zone at 850 hPa in Kaiyuan and its surrounding area (Figure 2a), and the wind speed did not reach the low-level jet intensity, but it was located near the northwest and west wind horizontal shear lines, and was located in the temperature ridge extending eastward at 850 hPa when there was a significant warm advection. The specific humidity at 850 hPa was only about 7 g/kg, and the humidity conditions in the lower atmosphere were poor.

The configuration of the 500-hPa low trough and the 850-hPa shear line indicates that the tornado circulation situation in the vicinity of northern Liaoning had an obvious forward tilt trough characteristic, which often indicates the possibility of strong convective weather such as thunderstorms, strong winds, and hail. From the temperature field configuration of the two pressure layers, it can be seen that the 500-hPa cold temperature trough in this area was superimposed on the 850-hPa warm ridge, with a temperature difference of over 29 ℃ between the two levels, resulting in a significant vertical temperature decrease rate.

The distribution of sea level pressure and surface temperature (Figure 2b and Figure 3) shows that there was a warm low-pressure development in northern Liaoning, and the Kaiyuan tornado occurred in the atmospheric pressure gradient area in the southeast of the low-pressure trough area, which was conducive to the maintenance of strong airflow in the near surface layer and boundary layer. Observations from the wind profiler (Figure 2d) and ground automatic stations (Figure 3) show that the near surface layer was southwest airflow, and the surface wind speed maintained 5-6 m/s. There was a strong wind speed zone in the boundary layer, which was conducive to transporting water vapor from the Bohai Sea and other places to the surrounding areas of Kaiyuan. The dew point at the surface in Kaiyuan increased from 14 ℃ at 08:00 to 19 ℃ at 16:00 and 17:00. The transport of warm and humid air and the effect of solar radiation increased the ground temperature to 29 ℃ at 17:00.

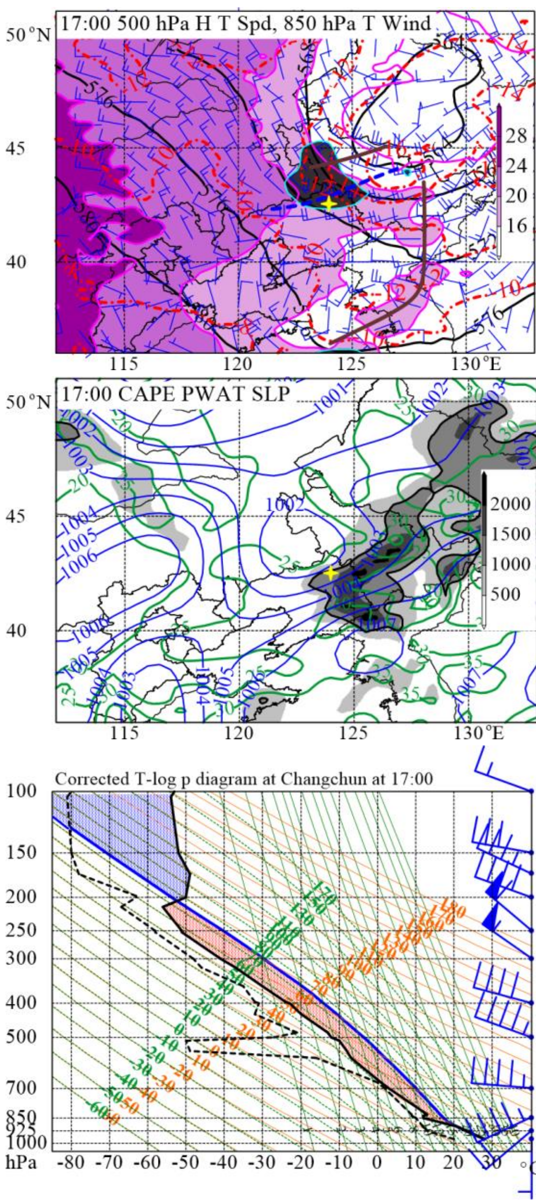
3.2 ENVIRONMENTAL CONDITIONS

Precipitable water (PW) and convective available potential energy (CAPE) of the CFSR data (Figure 2b) and surface temperature at 17:00 show that the Kaiyuan tornado occurred in the high temperature and high energy area, with CAPE value of about 1200 J/kg, but the PW value is small, only about 28 mm. The convective inhibition energy (CIN) at Kaiyuan was very low, only about 20 J/kg (not shown in the figure), which was conducive to triggering convection. The temperature at the surface was 29 ℃ and dew point was 19 ℃, which exceeded the corresponding median values of tornado in the United States (Grams et al., 2012).

The Changchun sounding observation at 08:00 was corrected using the surface observation temperature of 29 ℃ and dew point of 19 ℃ at Kaiyuan Station at 17:00, as shown in Figure 2c. The CAPE calculated using corrected sounding data reached 3450 J/kg, and the PW value was 33 mm. The CAPE value was significantly higher than the corresponding values given by the CFSR data, and also significantly exceeded the corresponding values of most tornadoes in the United States (Grams et al., 2012) and all Northeast China tornadoes, which was very conducive to the occurrence of strong tornadoes

(Anderson Frey et al., 2019). However, the corrected sounding map also shows that the height of uplift and condensation was relatively high, at about 870 hPa, which was a less favorable condition for the occurrence of tornadoes. But the CIN value was close to zero, which was a favorable condition for the occurrence of strong tornadoes according to the statistical results of Rasmussen and Blanchard (1998) and Grams et al. (2012).

At 17:00, the CFSR data show a temperature difference of 29 ℃ between 850hPa and 500hPa, with a significant vertical temperature decrease rate of approximately 6.8 ℃/km, which was comparable to the median vertical temperature decrease rate of significant tornadoes in the United States presented by Craven and Brooks (2004). The CFSR data (not shown in the figure) and Figure 2c both indicate that the altitude of the 0 ℃ layer was very low, about 3.6 km, which was conducive to the occurrence of hail.



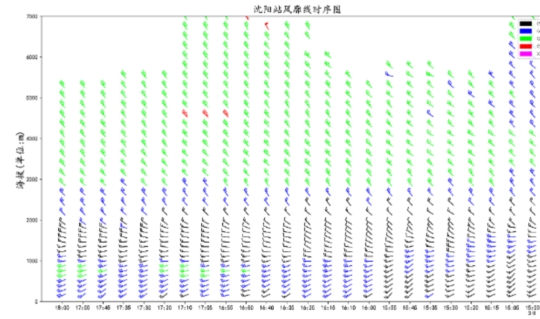


Figure 2 Synoptic situation and environmental conditions for 17:00 BT on 3 July, 2019

(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-℃ interval in ℃; 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 ℃; 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.)

The high relative humidity in the lower layers of the atmosphere was conducive to the downdraft of tornadic convective storms that are not too strong, which is conducive to the enhancement of the vertical vorticity near the ground (Doswell and Evan, 2003; Schultz et al, 2014). However, the relative humidity distribution of the sounding (Figure 2c) or the CFSR data shows that there were significant dry air layers below 850 hPa and above 500 hPa in the Kaiyuan atmosphere, which are the environmental conditions conducive to the strong downdraft generated by convective storms and the formation of high surface winds. The downdraft convective available potential energy (DCAPE) calculated by the corrected sounding data was 1060 J/kg, which belongs to the strong DCAPE value, and is conducive to strong downdraft generated by convective storm, but is not conducive to the tornado (Schultz et al, 2014; Zheng et al., 2017).

Tornadoes with intensity greater than F2/EF2 usually occur in the environment of strong vertical wind shear (Johns and Doswell, 1992; Craven and Brooks, 2004). The corresponding statistics in the United States show that the wind difference of 0 – 6 km generally exceeds 20 m/s (Weisman and Klemp, 1982; Grams et al., 2012). The CFSR data show that the vertical wind shear from Kaiyuan surface to 500 hPa (approximately 0 – 6 km) was 21 m/s, belonging to strong vertical wind shear (Zheng et al., 2017) and conducive to the occurrence of strong supercell tornado. Shenyang wind profiler observations (Figure 2d) had similar results.

The CFSR data show that at 17:00, the vertical wind shear from the surface to 925 hPa (approximately 0 – 1 km) around Kaiyuan was about 6 m/s, and the vertical wind shear from the surface to 850 hPa was about 8 m/s, which was weaker than the 0 – 1 km vertical wind shear of tornadoes exceeding F2/EF2 in the United States (Doswell and Evan, 2003).

However, it should be noted that the above analysis results based on CFSR data or corrected sounding data must be different from the actual environmental conditions. The wind profiler at Shenyang observed that the southwest wind speed in the boundary layer was significantly strengthened at about 16:00 (Figure 2d). In addition, the strong southwest wind of 5-6 m/s observed at ground automatic stations was conducive to the strengthening of the 0 – 1 km vertical wind shear and formed a coupling with the middle-level jet. The radial velocity field detected by the new generation weather radar can also be used to identify the difference between the actual wind field and the reanalysis data. At about 16:30, because the initiated convection of the tornadic storm was located in the north of Shenyang radar, and the environmental wind direction at 850 hPa was close to the west wind (Figure 2a), the radial velocity at 0.5° elevation (about 1-1.4 km altitude) in the area near the initiated convection was basically less than 5 m/s (not shown in the figure); From the radial velocity observation of Liaoyuan radar in Jilin Province, the initiated convection at this time was located in the west side of the radar, and the radial velocity at 0.5° elevation (about 1.2-1.6 km altitude) near the initiated convection was about 11-13 m/s (not shown in the figure). The radial velocity observed by Liaoyuan radar was closer to the actual environmental wind speed at 850 hPa. This shows that when the tornado actually occurred, considering that the southwest wind on the ground was 5-6 m/s, the vertical wind shear in the lower 0 – 1 km atmosphere was significantly greater than the value given by the CFSR data, which also significantly exceeded the corresponding USA tornado threshold of 10 m/s (Doswell and Evan, 2003). Therefore, the strong vertical wind shear in the lower atmosphere was conducive to the occurrence of the Kaiyuan tornado. However, this condition was not presented in the CFSR reanalysis data and the global numerical prediction field at that time.

Based on the above analysis, 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 (Schultz et al, 2014; Zheng et al, 2017). 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.

4. CONVECTION TRIGGERING, CONVECTIVE CLOUDS, AND LIGHTNING

The ground automatic station wind field shows that there was weak convergence of the wind field in different areas around Kaiyuan since 08:00 on 3 July (not shown in the figure), but there was no obvious convergence line yet. However, there was an obvious surface convergence line on the Inner Mongolia side near the border between Inner Mongolia and Liaoning, and the dew point temperature distribution shows that it was also a dry line. The visible image of the FY-4A satellite shows that there were many cumulus clouds with very low cloud tops around Kaiyuan since 08:00 on 3 July. However, by 15:00, none of these cumulus clouds were able to develop into deep convection. This indicates that although the temperature and humidity conditions near the surface during this period met the conditions for convective development, weak surface convergence (not shown in the figure), small CAPE values (not shown in the figure), and the suppression of large-scale downward motion made it difficult for deep convection to occur.

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. It should also be noted that the formation of this dry line was not caused by terrain, as the elevation differences between the stations on both sides of the dry line were not significant. The decrease in dew point at the north stations was caused by the northwest airflow transporting dry air, while the increase in dew point at the south stations was caused by the southwest airflow transporting wet air.

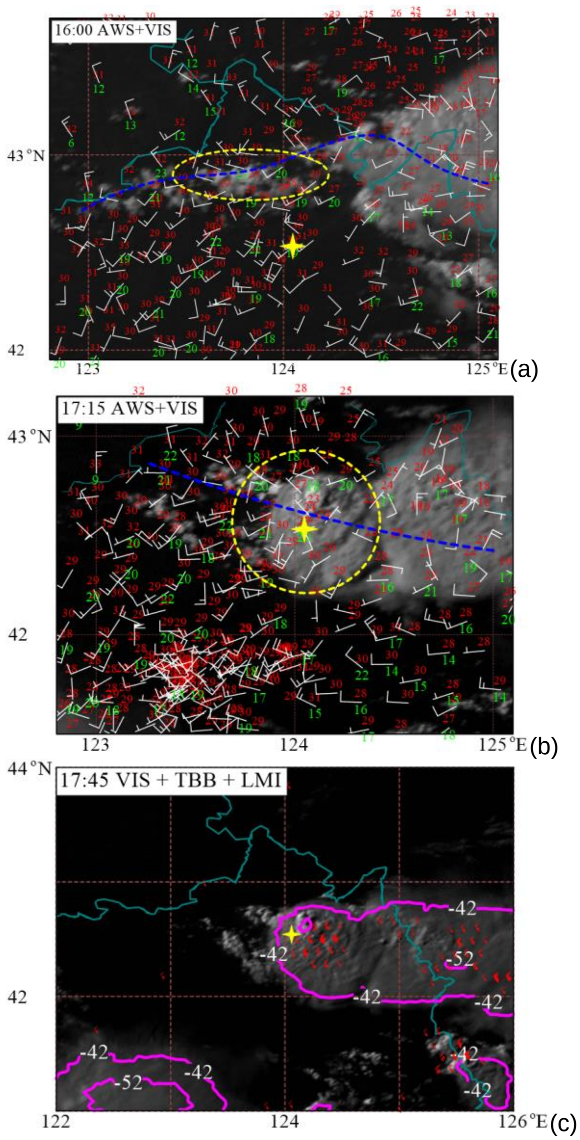


Figure 3 FY-4A and automatic weather station observations for 3 July
(a) 16:00 BT, (b) 17:15 BT, (c) 17:45 BT
In Figs. a and b, temperature (red digits), dewpoint (green digits) and winds from automatic weather stations and FY-4A enhanced visible images are presented (yellow star symbol denotes Kaiyuan 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-℃ and -52-℃ 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).

At 17:15, when the tornado formed (Figure 3b), the CAPE value in the Kaiyuan area continued to increase (Figure 2b), and at the same time, the dry line (convergence line) moved southward, significantly strengthening convection and moving southward to the vicinity of Kaiyuan. The convective storm caused a vortex like circulation on the ground. A circular convective cloud formed on the enhanced visible satellite image, with a very rough cloud top and significant features such as overshooting cloud tops and shadows. However, it can be distinguished that there was a clear boundary between the Kaiyuan convective storm and its eastern storms. But on infrared satellite images with lower spatial resolution, these convection appeared as a long strip meso-α-scale convective system had a minimum brightness temperature of around -51 ℃, and the tornado occurred in the western region with a large brightness temperature gradient. FY-4A LMI continued to observe some lightning activity (Figure 1c). The strongest reflectivity observed by Shenyang radar reached around 65 dBZ (not shown in the figure), and the storm was nearly mature. The damage survey indicates that the funnel cloud of the tornado hit the ground at approximately 17:17 (Zhang et al., 2020), andt the funnel cloud hanging and extending from the convective storm could already be seen before this.

At around 17:45 to 17:47, the tornado weakened and nearly disappeared. The infrared brightness temperature distribution and enhanced visible satellite image characteristics were similar to those at 17:15, but the lowest infrared brightness temperature was already below -52 ℃, and the visible satellite image shows fluctuating characteristics. Although NLLN did not detect cloud-to-ground flashes, FY-4A LMI observed more active lightning activity, indicating intense upward motion and very intense convection.

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.

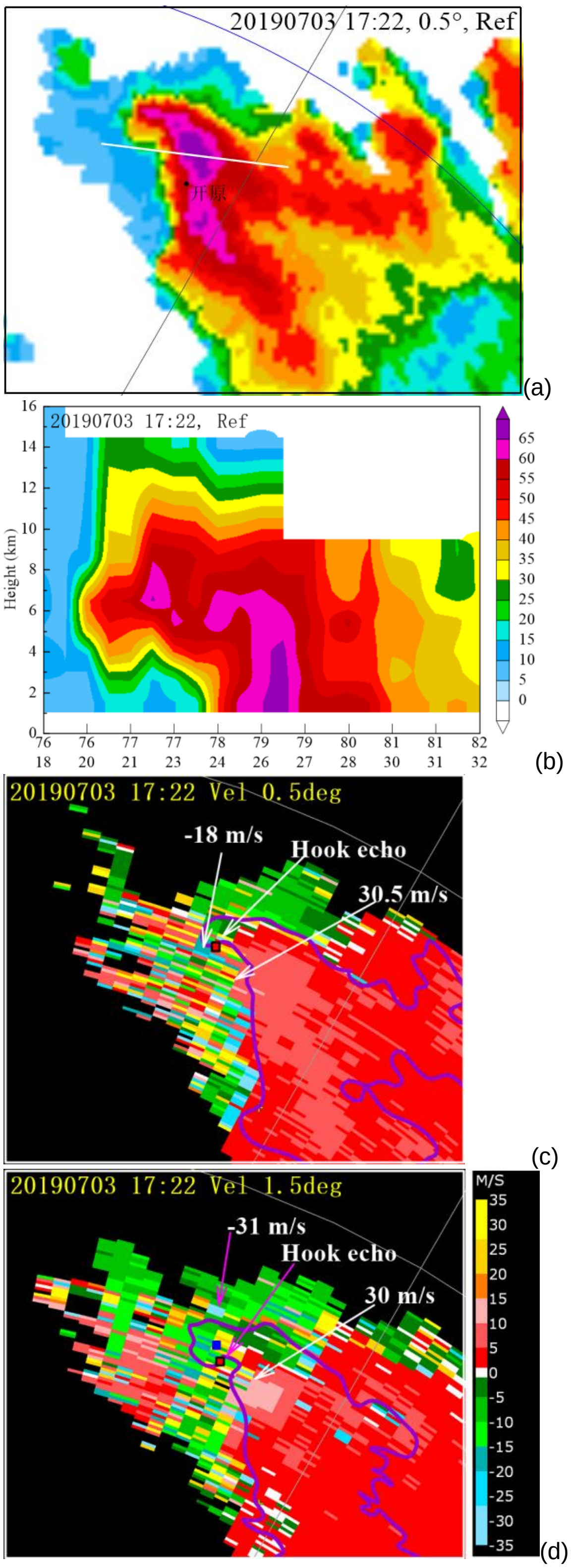


Figure 4 Shenyang radar observations at 17:22 BT on 3 July

(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)

At 17:17 (not shown in the figure) and 17:22 (Figure 4), when the tornado formed, the maximum reflectivity of the storm reached more than 65 dBZ, with hook echo characteristics, and the mesocyclone were more significant. These features continued to appear during the subsequent 5 scan periods until 17:50. Combined with the tornado position at the corresponding time obtained from the damage survey (Zhang et al., 2020), as shown in the tornadic supercell conceptual model given by Lemon and Doswell (1979), the tornado occurred at the top of the hook echo, near the interface between the rear downdraft and the front updraft (as shown by the red dots in Figure 4c and d). The path of the hook echo (not shown in the figure) was close to the tornado path obtained from the damage survey by Zhang et al. (2020). Although the distance from the Liaoyuan radar station in Jilin to the tornado was much longer than that of the Shenyang radar station, the observed tornado still had an obvious hook echo (not shown in the figure).

The cross section of reflectivity of Shenyang radar (Figure 4b) shows that the height of the strong reflectivity of the convective storm greater than 60 dBZ was more than 8 km, while the structure of "bounded weak echo " and "echo overhang" below the height of 4 km was also clear, indicating that the boundary layer had strong warm moisture inflow and very strong updraft. In addition, the strong reflectivity on the right side of cross section in in Figure 4b exceeded 65 dBZ and extended from the lowest level detected by the Shenyang radar from about 1 km to a height above 4 km. This is the radar echo feature that produces large hail, which is consistent with the hail witnessed in the urban area of Kaiyuan.

At 16:38, the Shenyang radar at elevation observed a clear mesocyclone in the convective storm that produced the Kaiyuan tornado, but at this time, there was no vortex feature at 0.5° elevation (not shown in the figure). As mentioned above, by 17:06, the radial velocity at elevations of 0.5 °, 1.5 ° and 2.4 ° had the characteristics of a mesocyclone (not shown in the figure), indicating that the low-level vortex of the convective storm was significantly strengthened compared with the previous period. The enhanced low-level vortex would not directly develop downward to the ground to form a tornado, but it would increase the pressure gradient force in the vertical direction of the supercell, thus would strengthen the updraft, which is conducive to the stretch of the vertical vorticity near the ground to form a tornado (Markowski and Richardson, 2014). The strengthening of the low-level vortex was closely related to the development of downdraft within the convective storm, as the cold pool formed by downdraft generated baroclinic horizontal vorticity, while the updraft tilted the baroclinic horizontal vorticity to form vertical vorticity, thereby strengthened the low-level vortex (Markowski and Richardson, 2009). The observation at automatic weather stations around Kaiyuan (not shown in the figure) did indeed show a decrease in surface temperature in the area affected by the convective storm at 17:05 compared to that at 17:00.

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.

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, as pointed out above, 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.

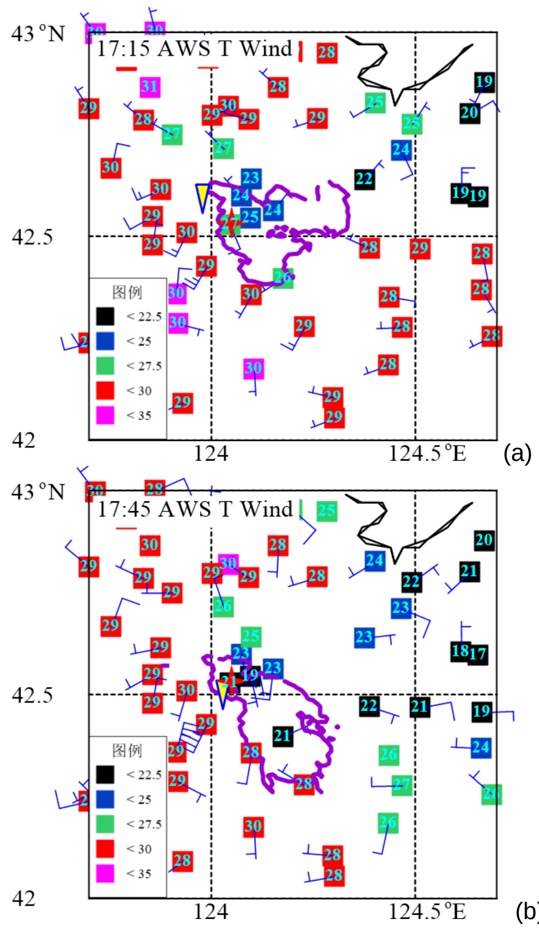


Figure 5 Temperatures and winds from automatic weather stations for 3 July
(Rectangles with different colors marked digits indicate temperatures. Red star symbol denotes the location of Kaiyuan meteorological station, yellow inverted triangle represents the location of hook echo at 0.5 ° elevation, and 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

However, at 17:45 (Figure 5b) when the tornado weakened and dissipated (Zhang et al., 2020), the hook echo were no longer as significant as in the previous period, indicating that the low-level updraft intensity of convective storms had weakened. The Shenyang radar observations at 1.5 ° elevation of show that the radial convergence in the middle layer near the area was strengthened, and the surface cold pool temperature significantly decreased and dropped to 19-21 °C, but the surrounding environmental temperature changed a little, still around 28-30 ° C. Therefore, the temperature difference between the cold pool and the environment increased to 7-11 ℃. Accordingly, the surface temperature distribution was very unfavorable for tornado maintenance. This also means that the strong downdraft caused strong cooling of the near surface air and formed a strong cold pool. Although the mesocyclone still existed at this time, the increase in negative buoyancy suppresses the vertical upward airflow near the near surface of the tornado vortex, which is not conducive to the maintenance of the strong vertical vorticity near the ground and ultimately causes the tornado to dissipate (Markowski and Richardson, 2009; Schultz et al., 2014; Zheng et al., 2017).

6. CONCLUSIONS

The main conclusions of this study are as follows:

1) The tornado occurred in the southwest side of a northeast cold vortex, behind the 500 hPa trough and in the large-scale subsidence movement area, with the characteristics of a forward tilt trough. There was a shear line between northwest wind and west wind at 850 hPa, and it was located in the large gradient area on the south side of the low sea-level pressure. The southwest wind speed at the surface was high, and the surface dew point was about 19 ℃, significantly higher than the corresponding values for most of Northeast China tornadoes.

2) The environmental conditions in Kaiyuan were favorable for thunderstorm, wind gust, hail, and also met the conditions of large CAPE value and strong 0 – 6 km vertical wind shear in favor of supercell, as well as the conditions of small CIN and strong 0 - 1 km vertical Wind shear in favor of strong tornado. However, the enhancement of 0 – 1 km vertical Wind shear was only detected in the radar radial velocity field and the Shenyang wind profiler observations, with mesoscale characteristics. The strong wind in the boundary layer was coupled with the 500-hPa jet, which met the strong vertical wind shear conditions in the lower and middle layers of the atmosphere required for the tornado generation.

3) The unfavorable environmental conditions for the occurrence of the Kaiyuan tornado are: the presence of dry layers in the middle and lower troposphere near Kaiyuan, low relative humidity, and high lift condensation level. However, before the formation of the tornado, precipitation occurred in the front of the convective storm in Kaiyuan and surrounding areas, causing rapid saturation of the atmosphere and a significant increase in relative humidity. This was beneficial for the hook echo area at the back of the convective storm moving to this area and generating a less strong cold pool, thus favorable for the formation of a tornado.

4) 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.

5) The radar data of Shenyang and Liaoyuan both show that the system causing the tornado was an isolated supercell. The radial velocities of Shenyang radar at 0.5 °and 1.5 ° elevations show that the maximum intensity of the mesocyclone was strong, and had a TVS characteristic. Before the formation of the supercell, the mesocyclone detected by Shenyang radar at 1.5 ° elevation was earlier than that observed at 0.5 °elevation. Considering the damage survey results, it is found that the tornado occurred at the hook echo, and in a small-scale surface vortex circulation observed at automatic weather stations.

6) The surface temperature observations of automatic weather stations show that at 17:15 at the initial stage of the tornado, the surface temperature difference between the cold pool and the environment was only about 2-4 ℃, and the cold pool was not too strong. But at 17:45, when the tornado nearly demised, the strong downdraft caused the surface temperature difference to exceed 7 ℃, suppressing the maintenance of vertical vorticity near the surface and causing the tornado to disappear.

7) 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)

REFERENCES

Craven, J. P., Brooks, H. E., 2004: Baseline climatology of sounding derived parameters associated with deep moist convection. *Natl. Wea. Dig.*, 28, 13–24.

Doswell, C. A., Evans, J. S., 2003: Proximity sounding analysis for derechos and supercells: An assessment of similarities and differences. *Atmos. Res.*, 67–68, 117–133.

Grams, J. S., Thompson, R. L., Snively, D. V., et al., 2012: A climatology and comparison of parameters for significant tornado events in the United States. *Wea. Forecasting*, 27, 106–123.

Johns, R. H., Doswell, C. A., 1992: Severe local storms forecasting. *Wea. Forecasting*, 7, 588- 612.

Lemon, L. R., Doswell III, C. A., 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.*, 107, 1184–1197.

Markowski, P. M., Richardson, Y. P., 2009: Tornadogenesis: Our current understanding, forecasting considerations, and questions to guide future research. *Atmos. Res.*, 93, 3–10.

Markowski, P. M., Richardson, Y. P., 2014. The influence of environmental low-level shear and cold pools on tornadogenesis: Insights from idealized simulations. *J. Atmos. Sci.*, 71, 243–275.

Rasmussen, E. N., Blanchard, D. O., 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters[J]. *Wea. Forecasting*, 13, 1148–1164.

Schultz, D. M., Richardson, Y. P., Markowski, P. M., et al., 2014: Tornadoes in the central United States and the “Clash of Air Masses” . *Bull. Amer. Meteor. Soc.*, 95, 1704–1712.

Wang, X. M., Yu, X. D., Zhou, X. G., 2015: Study of Northeast China tornadoes: The environmental characteristics. *Acta Meteorologica Sinica*, 73, 425-441(in Chinese).

Zhang, T., Guan, L., Zheng, Y. G., et al., 2020: Damage survey of the 3 July 2019 Kaiyuan tornado in Liaoning Province and its evolution revealed by disaster. *Meteor. Mon.*, 46, 603-617 (in Chinese).

Zheng, Y. G., Tao, Z. Y., Yu, X. D., 2017: Some essential issues of severe convective weather forecasting. *Meteor. Mon.*, 43, 641–652 (in Chinese).

Weisman, M. L., Klemp, J. B., 1982: The dependence of numerically simulated convective storms on wind shear and buoyancy. *Mon. Wea. Rev.*, 110, 504–520.