Stage characteristics and causes of a mixed severe convective weather process

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Abstract. Based on the conventional observation data, the intensive automatic weather station data, the 1°×1° Final Operational Global Analysis data and the Doppler radar data, this study analyzes the stage characteristics and causes of a mixed severe convective weather process in Hunan Province from April 23 to 24, 2019. The results show that this severe convective weather mainly has two stages. In the first stage, the disastrous weather is mainly the short-term heavy precipitation. The convective weather in this stage is severe mixed convective weather process forced by warm advection. The short-term heavy precipitation is mainly caused by the continuous influence of multi-cell storms. The disastrous weather in the second stage is mainly the thunderstorm gale. It is a squall line process forced by upper-level cold advection. Besides, there is apparent mid-altitude radial convergence and high wind core on the radial velocity map. The surface convergence line is the primary dynamic uplift condition triggering the mixed convection in the first stage, and there are several abnormal low centers of three-hour pressure change in the western and southern Hunan. The severe convective weather process in the second stage is mainly triggered by the forward-tilted trough. The dynamic conditions and energy conditions are favourable for the convections at both stages. Compared with the second stage, water vapor is more abundant in the first stage, which is more favorable for the occurrence of short-term heavy precipitation. The three-body scatter spike of hail is not obvious before the formation of the squall line. The early warning signals are mainly the height of the strong echo and vertical integrated liquid water content, both of which increase significantly before the formation of the squall line. The early warning of thunderstorm gale after the formation of the squall line can be issued in advance by monitoring the low-level wind in the downstream areas of the squall line.

1. Introduction

Severe convective weather is featured by small scale and short duration, and occurs suddenly. The forecast and research on severe convective weather have always been the concerns of meteorologists [1-3], and it is also a difficulty in operational weather forecast. Although the temperature gradually increases in spring in Hunan Province, the cold air from the north still frequently affects Hunan, and causes strong convective weather such as gale, hails and rainstorms. In summer, the convective weather occurs more frequently than in other seasons due to the warm-moist atmospheric environment. Many scholars [4-7] have comprehensively analyzed the background, potential energy conditions and triggering mechanisms of severe convective weather in Hunan in spring and summer. They used radar data to rapidly identify heavy precipitation echoes and supercells, discussed the practicability of early
warning, and explored the nowcasting signals that could be used for early warning. Cai et al \[8\] divided the weather situation configuration of thunderstorm gale into low-level warm advection forcing type, baroclinic frontogenesis type, quasi barotropic type and high-level cold advection forcing type.

During April 23–24, 2019, a mixed severe convective weather process occurred in Hunan, with short-term heavy precipitation and thunderstorm gale. It is featured by a wide influence range, high intensity, long duration and overlapping disaster-affected areas. This weather process brought strong wind and hail disasters, resulting in the collapses of river banks, water slopes and dams, house damage and crop damage such as tobacco and vegetables in some areas. In this study, the weather situation analysis and physical quantity diagnosis of the process are carried out by using the conventional surface and upper-level observation data and the National Centers for Environmental Prediction/National Center for Atmospheric Research 1°×1° reanalysis data with an interval of 6 h. Moreover, based on the radar data, we further discuss the causes of the strong convective weather.

2. Overview of the severe convective process

From 08:00 on April 23 to 08:00 on April 25, 2019, a wide range of severe convective weather occurred to the south of central Hunan. The main influence periods are from 08:00 to 15:00 on April 23, from 23:00 on April 23 to 08:00 on April 24, and from 19:00 on April 24 to 06:00 on April 25 (Table 1). As the convection in the daytime of April 23 was weak, this study mainly focuses on the latter two periods, which are called the first stage and the second stage, respectively. Meteorological stations observed 22 thunderstorm gales in the first stage and 58 in the second stage. The maximum wind speed appeared at Xiucailing station in Puman Town, Jiahe County at 00:49 on April 25, reaching 31.1 m·s\(^{-1}\) and level 11. There were eight counties with local hail, mainly concentrated in the first stage. Among them, four counties in western Hunan had the hail with the largest diameter of 20 mm, namely, Fenghuang County (23:48–23:51 on April 23), Mayang County (23:45–23:55 on April 23), Chenxi County (01:00–01:10 on April 24) and Zhongfang County (01:10–01:15 on April 24). Two counties in southeastern Hunan had small-scale hail, namely, Jiahe County (around 00:00 on April 25) and Guiyang County (06:36–06:41 on April 24). Meteorological stations observed 441 short-term heavy precipitation events. Among them, 234 events occurred in the first stage, with the maximum hourly rainfall of 61.4 mm occurring at Haihua Experimental School station in Chenxi (00:00–01:00 on April 24). Besides, 149 events occurred in the second stage, with the maximum hourly rainfall of 54.2 occurring at Sugu Village, Guanqiao Town, Liuyang City (05:00–06:00 on April 25). In summary, the frequency and intensity of thunderstorm gale in the second stage were higher than those in the first stage. However, the short-term heavy precipitation in the first stage has larger intensity and wider range than in the second stage. In the early morning of April 24, a hail event occurred in western Hunan. Therefore, the strong convective weather in the first stage was mainly short-term heavy precipitation, local hail and thunderstorm gale, but the second stage was dominated by thunderstorm gale (Figure 1).

| Periods                  | Thunderstorm gale (station observations) | Hail (county) | Short-term heavy precipitation (station observations) |
|--------------------------|------------------------------------------|---------------|------------------------------------------------------|
| 23:00 on April 23 to 08:00 on April 24 (the first stage) | 22                                       | 5             | 234                                                  |
| 19:00 on April 24 to 06:00 on April 25 (the second stage) | 58                                       | 1             | 149                                                  |
| Total                    | 80                                       | 6             | 383                                                  |

Table 1. Types and periods of the severe convective weather.
3. Characteristics of radar echoes and the early-warning respect

3.1. The first stage

The evolution characteristics of radar echoes observed at Zhangjiajie (Figure 2) show that the echoes were mainly the cumuliform-stratiform-mixed precipitation echoes in the first stage. The area with radar echoes larger than 35 dBZ reached 70 km×50 km, and the maximum reflectivity factor reached 60 dBZ. The echoes moved eastward and southward slowly.

At 22:54 on April 23, a strong storm cell was generated on the boundary between Hunan Province and Guizhou Province, and moved eastward slowly. At 23:36, the three-body scatter spike (the circle in Figure 2a) was detected in the radial direction of the storm cell (the southwest side of the storm cell), but it was not prominent. It is tentatively inferred that there were cumuliform-stratiform-mixed precipitation echoes on the western side of the three-body scatter spike, and thus the long spike was covered. At that time, the maximum reflectivity factor of the storm cell at the elevation of 0.5° reached 60 dBZ and the vertical height extended to 9.4 km (figure omitted). For the vertical integrated liquid water content (VIL) map corresponding to the moving track of the storm cell, the VIL increased to more than 60 kg·m⁻² at 23:12 (Figure 2b). Thereafter, the high VIL above 60 kg·m⁻² is sustained for five volume scans (23:12–23:42), with the echo-top height exceeding 14 km (Figure 2c). It is evident that the convection developed vigorously, and strong hail clouds already developed at this stage. The vertical cross-section of the reflectivity factor at Fenghuang County (Figure 2d) shows that the strong echo larger than 55 dBZ extended to the height of the −20°C layer, with a distinct overhanging structure.

According to the disaster investigation, it can be found that strong hail occurred in Fenghuang County at 00:00 on April 24, with the maximum size similar to an egg. Then, the storm affected Mayang County and also brought hail. A bow echo then developed in front of the mixed precipitation echoes, and crossed over Xiangxi Prefecture, northern Huaihua City, Shaoyang City and other places, resulting in regional short-term heavy precipitation.
Figure 2. (a) Composite reflectivity factor at 23:36, (b) VIL at 23:12, (c) echo-top height at 23:12 and (d) vertical cross-section of reflectivity factor at 23:36 on April 23 observed by the Zhangjiajie radar.

At 00:48 on April 24, another storm cell began to affect Chenxi County. Meanwhile, an obvious mesocyclone was detected on the radial velocity map (Figure 3a), with a rotation speed of 12.3 m s\(^{-1}\) (medium intensity). Its bottom extended downward to 4.1 km and its top extended to 7.7 km. Generally, the higher the vertical height of the mesocyclone is, the stronger the updraft is, and the more intense the hail collision growth in the air is. The storm cell had obvious bow echo characteristics (Figure 3b). The backward inflow gap and forward inflow gap indicated the existence of strong inflow and outflow. Moreover, multiple storm cells were concentrated on the southwest side of the bow echo, indicating a vigorous convection development. The continuous influence of the bow echo and multiple storm cells caused the short-term heavy precipitation in Huaihua, Fenghuang, Mayang and Xupu successively.

Figure 3. (a) Radial velocity and (b) composite reflectivity factor of Zhangjiajie radar at 1.5\(^{\circ}\) elevation angle at 00:48 on April 24.

In summary, the hail early warning is difficult in the first stage. This is because the three-body scatter spike of strong hail is obscured due to the restriction of the detection conditions and environmental fields. Moreover, Fenghuang and Mayang are located at a radial distance of 230 km from the radar station, and the elevation of the Zhangjiajie radar is as high as 1.48 km. Because of the geographical location, Fenghuang and Mayang are in the purple area on the radial velocity map. Thus, the radial velocity in these areas cannot be judged. So even if mesocyclones occur, it is impossible to observe and
identify them. Hence, the early-warning respect is mainly on the height of the strong echo and the abrupt increase of the strong VIL. However, the early warning time is still relatively limited, less than 15 minutes.

3.2. The second stage
The disastrous weather in the second stage was mainly thunderstorm gale. The reflectivity factor figure shows that the bow echo developed significantly in western Hunan at 20:34 on April 24 (Figure 4a), causing thunderstorm gale in Jingzhou County and Tongdao County. The radial velocity map (Figure 4b) shows that the negative velocity area was larger than the positive velocity area in the first range circle of the Yongzhou radar. Meanwhile, there were high-value areas of velocity below the 1 km height within the 25 km range. As can be seen, there was significant convergence in the lower and middle levels in the downstream areas. After ten volume scans, the squall line moved eastward and southward slowly. In addition, new supercells constantly merged at the southern end of the squall line (circle in Figure 4c) and travelled northeastward, resulting in the continuous growth of the southern end of the squall line. On the corresponding velocity map, there was obvious radial convergence in the middle level associated with the squall line echo (circle in Figure 4d) and gale centers on the southern side corresponding to supercells. The squall line broke at 22:34, and the northern part of the broken squall line began to affect western Yongzhou (Figure 4e). There was an obvious gale core (circle in Figure 4f) in the middle layer of the low elevation velocity map. In addition, the wind convergence was more significant in the first distance circle. Therefore, the thunderstorm gale occurred successively in the urban areas of Yongzhou, Dao County, Shuangpai County and Jianghua County (23:15–23:50).

Figure 4. Composite reflectivity (left) and radial velocity at 1.5° elevation angle (right) of the Yongzhou radar at (a, b) 20:34, (c, d) 21:34 and (e, f) 22:34 on April 24.

The vertical wind profile (Figure 6) from Yongzhou radar shows that an upper-level trough passed through in the second stage. Before 23:34 (Figure 5a), the vertical wind profile showed a consistent
southwesterly wind from the upper levels to low levels, and the wind speed reached 12 m·s$^{-1}$ above 1.5 km. From 23:50, the southwesterly wind turned to the westerly wind at the height of 4–6 km (Figure 5b). At the same time, the weak southwesterly wind turned to the southeasterly wind at the 0.3 km height, and the wind speed increased. Besides, it can be seen that the vertical wind shear increased significantly and rotated clockwise, indicating the development of warm advection. From 00:22 on April 25, the westerly wind at the height of 4–6 km turned to a northwesterly wind (Figure 5c). The evolution of the wind profile reveals that the passage of the upper-level trough was closely related to the generation and movement of the squall line.

Figure 5. Vertical wind profile of Yongzhou radar (a) at 23:04 and (b) 23:50 on April 24 and (c) 00:46 on April 25.

In summary, the main cause of the thunderstorm gale in southern Hunan is the passage of the squall line. If the squall line is monitored in the upstream area and the gale has also appeared in the corresponding observation, meanwhile there is convergence of wind field in downstream areas, then we could release the thunderstorm-gale early-warning in advance.

4. Potential of severe convective weather

4.1. Large-scale circulation background

From the circulation configuration at 20:00 on April 23 (Figure 6a), it can be found that there was a long and narrow upper level jet crossing over Guizhou-Xiangxi-Yangtze River Delta at 200 hPa. Hunan was located in the strong divergence area on the right side of the upper level jet entrance region. At 500 hPa, the middle-high latitudes were controlled by two troughs and one ridge, and the subtropical high was in blocks in an east-west direction. In addition, there was a trough in the area from Chongqing to southwestern Guizhou, and Hunan was in front of the cold trough. At 850 hPa, the southwest vortex was located in northern Guizhou, and one end of the warm shear in the eastern section of the herringbone shear line extended to the central and western Hunan. Simultaneously, the vortex moved eastward and southward to the warm-humid areas of western and southern Hunan, and was significantly strengthened. To wee hours on April 24, the range of convective cloud cluster expanded and its intensity increased. For the low level wind field, the southwest jet crossed from northern Guangxi to Hunan at 700 hPa and 850 hPa, with the abundant water vapor and unstable energy transported to Hunan. In terms of humidity conditions, central and southern Hunan was in the significant wet zone at 850 hPa and the dry tongue at 500 hPa. Such humidity condition indicated that the dry-cold air intrusion at middle levels was a favorable condition for triggering strong convections. It also indicated that the atmosphere was unstable, with warm-wet air at upper levels and dry-cold air at low levels in the first stage. Moreover, the temperature ridge at 850 hPa was located from eastern Guizhou to western Hunan, with a vertical temperature lapse rate of more than 25°C in western and southern Hunan. This result indicated that western Hunan was located in the strongest convergence area in front of the warm ridge, which was also an essential cause for hail and other disastrous weather. For the weather situation configuration, the strong convection at this stage belonged to the low-level warm advection forcing type proposed by Xu et al.
Figure 6. Configuration of main upper-level circulation systems at (a) 20:00 on April 23 and (b) 20:00 on April 24, 2019. Purple, dark red, light red and gray arrows are the jets at 200 hPa, 700 hPa, 850 hPa jet and 925 hPa, respectively. The brown single line denotes the 500 hPa trough, the brown parallel line 700 hPa shear line, the red parallel line 850 hPa shear line, the gray arrow 925 hPa shear line, the blue triangle point line 500 hPa cold trough, the brown dotted line 850 hPa temperature ridge, the green dotted line 850 hPa significant wet zone, and the black solid lines the 588 contours at 500 hPa.

For the main circulation system configuration at 20:00 on April 24 (Figure 6b), the 200 hPa upper-level jet moved southward and was located in the areas from western Hunan to southern Jiangxi Province and Yangtze River Delta. Meanwhile, the southern Hunan was located in the strong divergence area on the right side of the upper-level jet entrance range. The 500 hPa upper-level trough moved to central Hunan, and the temperature trough lagged behind the height trough. The 700 hPa trough was located between Chongqing and northwestern Guizhou, and Hunan was in the positive vorticity advection in front of the trough. At that time, the forward-tilted trough provided more favorable dynamic conditions for the strong convections in the second stage. The 700 hPa southwest jet was located in southern Hunan, with the maximum wind speed of the jet axis reaching 16 m/s. The shear lines at 850 hPa and 925 hPa were both in southern Hunan, and the ultra-low-level shear line was conducive to enhancing the ascending movement. Besides, the terrain of the Nanling Mountains strengthened the convergence. In terms of humidity conditions, southern Hunan was located in the wet zone at 850 hPa and the dry tongue at 500 hPa. The unstable stratification with dry air at upper levels and wet air at low levels provided favorable environmental conditions for convections. The warm temperature ridge at 850 hPa and the cold trough at 500 hPa converged in southeastern Hunan, and the convergence of cold and warm air was beneficial to triggering convections. The strong convections at this stage were consistent with the upper-level cold advection forcing type proposed by Xu et al.

Based on the comprehensive analysis of the 3-hour upper-level chart and the disaster weather observations, it can be found that the 500 hPa trough was located from Huaihua to northern Guangxi at 20:00 on April 24, and the 700 hPa trough was at the boundary of Hunan and Guizhou. For the disaster weather records, the thunderstorm gale with 17.5 m·s⁻¹ speed occurred in Jingzhou at 20:00, and the thunderstorm gale with 18.2 m·s⁻¹ speed occurred in Tongdao at 21:00. This result indicated that the thunderstorm gale appeared behind the 500 hPa trough and in front of the 700 hPa trough (Figure 7). When the 700 hPa trough passed through ultimately, the weather in southeastern Hunan turned clear.
4.2. Favorable environment field

By analyzing the sounding data at two representative stations (Huaihua station and Chenzhou station) in the two stages, it is found that there was a significant inversion in low levels at 20:00 on April 23. After revision the convective available potential energy (CAPE) increased significantly (Table 2). The two stages had several similarities as follows. Heights of the 0°C level and −20°C level were suitable, with a slight difference in the two stages, which was beneficial to hail occurrence. There was an obvious dry intrusion in the middle level. The CAPE were large, more than 1000 J·kg⁻¹. The Showalter index (SI) was negative, less than −1.8°C. Moreover, there was a jet stream at 500 hPa, which was conducive to the downward momentum transportation. The 0–6 km vertical wind shear reached the strong level, favoring the generation of strong storms (supercells). The K index had little significance in indicating except for that at Huaihua station at 20:00 on April 24.

However, there were still several differences. For example, the CAPE in the first stage was larger, which was more conducive to large-scale hail. At 0–2 km height, the vertical wind shear is significantly larger in the first stage than in the second stage, which was more conducive to severe thunderstorms (supercells). In the first stage, the wind rotated clockwise with the height and then rotated anticlockwise when above 600 hPa. It meant that there was warm advection in the low levels and cold advection in the middle levels in the first stage, with a more unstable stratification than in the second stage. In the second stage, the wind rotated clockwise with the height, and there was warm advection in the whole layer. The relative humidity in low levels was higher in the first stage, more favorable for the occurrence of short-term heavy precipitation. However, the wet layer in southeastern Hunan was shallow in the second stage, and the short-term heavy precipitation was not significant. Moreover, the stratification curve in Chenzhou was characterized by the shape of double-trumpet, more conducive to thunderstorm gales in southeastern Hunan.

Table 2. Comparison of convective indexes between Huaihua station and Chenzhou station at 20:00 on April 23 and 20:00 on April 24.

|            | Huaihua station |            |            |            |            |            |            |            |
|------------|-----------------|------------|------------|------------|------------|------------|------------|
|            | K (°C)          | SI (°C)    | CAPE (J·kg⁻¹) | DCAPE (J·kg⁻¹) | 0–6 km vertical wind shear (m·s⁻¹) | 0–2 km vertical wind shear (m·s⁻¹) | 0°C layer (km) | −20°C layer (km) |
| 20:00 on April 23 | 27 | −4.7 | 1612.7 | 72.2 | 21 | 12 | 4.7 | 7.6 |
| 20:00 on April 24 | 46.2 | −8 | 1264.2 | 4.8 | 10 | 3.5 | 4.3 | 7.2 |
|            | Chenzhou station |            |            |            |            |            |            |            |
|            | K (°C)          | SI (°C)    | CAPE (J·kg⁻¹) | DCAPE (J·kg⁻¹) | 0–6 km vertical wind shear (m·s⁻¹) | 0–2 km vertical wind shear (m·s⁻¹) | 0°C layer (km) | −20°C layer (km) |
| 20:00 on April 23 | 28 | −3 | 1068.3 | 2.4 | 21 | 12 | 5.0 | 7.7 |
| 20:00 on April 24 | 31 | −2 | 1551.1 | 0.1 | 22 | 4 | 4.9 | 7.5 |
4.3. Favourable triggering conditions

The surface convergence line was the main dynamic condition triggering the mixed convection in the first stage from the night of April 23 to the early morning of April 24, the surface convergence line north-south migrated in southern Hunan, with the maximum amplitude not exceeding three latitudes. Due to the uplift effect caused by the topography of the northern Nanling Mountains and Xuefeng Mountains, the convective weather mainly occurred on the windward side of mountains. By analyzing the 3-hour continuous pressure change, pressure and wind field data from 23:00 on April 23 to 08:00 on April 24 (figure omitted), it can be found that the 3-hour pressure change was still positive at 23:00 on April 23 and rapidly turned to negative in western and southern Hunan at 02:00 on April 24. The negative pressure change appeared in many areas at 05:00 on April 24. The pressure change of most parts of Hunan turned to positive again at 08:00 on April 24. This result indicated that a small-scale low-pressure system affected western and central Hunan in the wee hours on April 24. By comparing the climatic standard deviation of the 3-hour pressure change at each time in the first stage with those of Xu's statistics (Table 3), it can be found that a large area of abnormal low centers of 3-hour pressure change appeared in western and southern Hunan during the convection development in the wee hours on April 24, which was conducive to promoting the development and strengthening of the mesoscale systems. The surface weather chart also showed that the small-scale low-pressure system moved from Guizhou to Xiangxi Prefecture, and then moved southward to central Huaihua. Note that there was also a small-scale low-pressure in southern Hunan. This result indicated that the small-scale low-pressure system accompanied by the surface convergence line was the main triggering mechanism of the strong convections in the first stage.

On the surface weather chart at 14:00 on April 24 (figure omitted), Hunan as a whole was located in a low-pressure area, with temperature exceeding 30°C. Thus, the thermal instability in the region was significantly enhanced. The thunderstorm gales mainly occurred in the area near 850 hPa warm ridge with high surface temperature, indicating that a large amount of unstable energy was triggered and released in this area. The hourly data from intensive automatic weather station shows that the low-pressure system was generated in southwestern Hunan at 19:00 on April 24 and gradually moved southeastward. From 19:00 to 22:00 on April 24, it was located at the southern foot of the Xuefeng Mountains. Due to the terrain friction, the low-pressure system moved slowly and accelerated after climbing over the mountain. After 23:00 on April 24, the low-pressure system arrived near Nanling Mountains, and its movement slowed down, bringing thunderstorm gale to southeastern Hunan. From 00:00 to 04:00, the low-pressure system moved eastward along the surface convergence line. During this process, the near-surface pressure dropped due to the blocking effect of the mountains and the surface convergence line that strengthened the upward movement.

| Table 3. Standard deviation of 3-hour pressure change at each time of April 24. |
|-------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| ∆P₃  | 02:00 | 05:00 | 08:00 | 11:00 | 14:00 | 17:00 |
| Standard deviation | 0.7–0.8 | 0.7–0.9 | 0.7–0.8 | 0.7–0.8 | 0.9–1.0 | 0.8–1.0 |

5. Conclusions

Based on the comprehensive analyses of the mixed convective weather in Hunan from April 23 to 24, 2019, the following conclusions are drawn.

The severe convective weather can be divided into two stages. The disastrous weather in the first stage was mainly the short-term heavy precipitation, accompanied by local thunderstorm gale and small-scale hail. This weather process in the first stage belongs to the warm advection forcing type. The severe convective weather in the second stage was mainly thunderstorm gale, with scattered short-term heavy precipitation, which belongs to the upper-level cold advection forcing type.
The first stage was dominated by broad mixed precipitation echoes, while the second stage was dominated by typical linear convective echoes. Besides, new supercells constantly merged into the southern end of the squall line and travelled northeastward, resulting in the continuous growth and development of the squall line on its southern end. The radar figures in the second stage were featured by the bow echo, the mid-altitude radial convergence, the low-level divergence, the high-value area of the velocity and the velocity ambiguity.

The surface convergence line was the main dynamic uplifting condition triggering the mixed convection in the first stage. From the night of April 23 to the early morning of April 24, the surface convergence line north-south migrated in southern Hunan, with the maximum amplitude not exceeding three latitudes. The severe convective weather in the second stage occurred after the upper-level low-pressure trough moved eastward and turned into a forward-tilted trough. Linear convections were generated near the upper-level trough. Simultaneously, in the low-level unstable energy area the linear convections developed into a squall line during the eastward movement of the forward-tilted trough. Then, the thunderstorm gale swept the whole southern Hunan.

The energy conditions and dynamic conditions were favorable for the convections in both stages. In the first stage, the water vapor was more abundant than in the second stage, with the near-surface specific humidity reaching 16 g·kg\(^{-1}\). The unstable energy area was mainly distributed in western Hunan. In the second stage, the unstable energy in southeastern Hunan was larger, with the CAPE value of more than 2000 J·kg\(^{-1}\).

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