Analysis of Characteristics of Hail Disaster and a Typical Hail Suppression Process in Qujing City

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Abstract Based on the data of hail disaster in Qujing City and the detection data of the new generation of Doppler weather radar, the spatial and temporal distribution characteristics of hail disaster and hail suppression operations in Qujing City were analyzed statistically, and the hail suppression operations of a typical cell case was analyzed. The results showed that the number of hail days and hail frequency showed an increasing trend in Qujing City from 2017 to 2022, and the number of artificial hail suppression operations increased accordingly. Hail disaster occurred most frequently in Xuanwei City. Through the analysis of hail suppression operations of a typical cell case, it is found that the operations were timely, and the location was reasonable. The ammunition used was sufficient, and the overall effect of the hail suppression operations was good.

Key words Hail disaster; Hail suppression; Operation; Qujing

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Hail, which is one of the most frequent disasters in summer in Yunnan, has the characteristics of strong local nature, concentrated occurrence time, short duration and strong sudden occurrence, and is easy to cause great harm to agricultural production and human and animal safety. On April 30, 2021, hail disaster happened suddenly in Luoping County, Qujing City, so that more than 6 000 hm^2 of various crops was affected, and about 93 000 people were affected. Direct economic losses amounted to 96 million yuan. Relevant scholars have carried out researches on the formation mechanism, growth process, activity characteristics, early warning indicators, mechanism and technology of hail suppression, *etc*. For instance, Zhang Guoqing *et al*. [1] concluded the microstructure and growth mechanism of hail in Qinghai by analyzing hail spectrum, ice crystal, bubble structure and isotope of hailstones. Peng Qiyang *et al*. [2-3] analyzed the characteristics of hail activity in different regions of China. Zhang Shifen *et al*. [4-8] conducted a correlation analysis of thresholds of the maximum echo intensity, maximum echo top height, echo top height and 0 ℃ layer height difference, providing a reference for the early warning of hail disaster.

Qujing City, which is located in the east of Yunnan Province, has the highest frequency of hail and the largest planting area of flue-cured tobacco in Yunnan Province. Hail mostly occurs from June to August. As the high incidence period of hail disaster almost coincides with the key growth period of flue-cured tobacco and other crops[9-10], sudden hail will cause serious harm to them, resulting in huge economic losses, so the hail suppression situation is very serious. Artificial hail suppression operations in Qujing City began in 1999, and the large-scale weather modification operation began in 2001. By 2022, 122 hail suppression operation points have been set up in the city's flue-cured tobacco planting areas, providing a favorable guarantee for disaster prevention and reduction in regional flue-cured tobacco production.

1 Data sources

The data of hail disaster came from the observation data collected and reported by 9 counties (cities and districts) and 122 weather modification operation points in Qujing City, Yunnan Province, including detailed records of the specific hail disaster locations (towns, towns or streets and villages where hail fell), occurrence time (accurate to minutes), and duration. The radar echo data comes from the Doppler radar detection data of radar stations in Qujing City, Yunnan Province, and the information of weather modification operation came from the actual data of 122 fixed operation points in Qujing City. Since the new generation of Doppler radar in Qujing City was built in 2016, only the data from 2017 to 2022 were used for relevant analysis.

2 Spatial and temporal distribution characteristics of hail disaster in Qujing City

2.1 Temporal distribution of hail disaster in Qujing City The data of hail disaster in Qujing City from 2017 to 2022 was used for statistical analysis. The day with one or more times of hail was recorded as one hail day, and the number of hail weather processes was recorded as *N*. If hail occurred at n stations on the same hail day, hail frequency was recorded as n. There were 135 hail days and 367 hail weather processes in the past 6 years. As can be seen from Fig. 1a, the number of hail days in Qujing City showed a significant increasing trend. The number of hail days in 2018 was the least, only 18 d. The number of hail days in 2022 was up to 31 d, and it happened in 2022. Seen from Fig. 1b, hail frequency in Qujing City in recent 6 years showed a decreasing trend. Due to

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the construction of Doppler radar, the ability of weather modification has been improved, which reflects the effectiveness of weather modification operation to a certain extent.

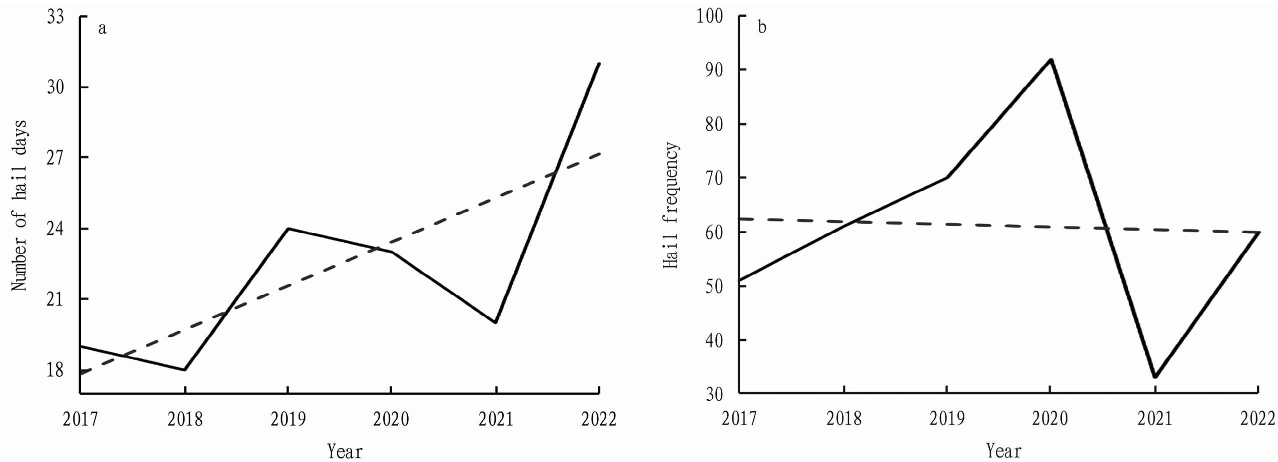

Fig. 1 Changing trends of hail days and frequency in Qujing City from 2017 to 2022

As shown in Fig. 2, hail disaster might occur in Qujing City throughout the year, and was frequent from May to August, accounting for more than 80% of the total number of hail days and hail frequency in the whole year, while hail disaster was rare in winter. Seen from the monthly distribution of annual average number of hail days in each county (Fig. 3), the number of hail days was the largest in Xuanwei City, and the annual average number of hail days in July and August was the largest, reaching 2.3 d. In Huize County and Luoping County, hail appeared frequently in July, and there was still a high probability of hail in Xuanwei City in April and November.

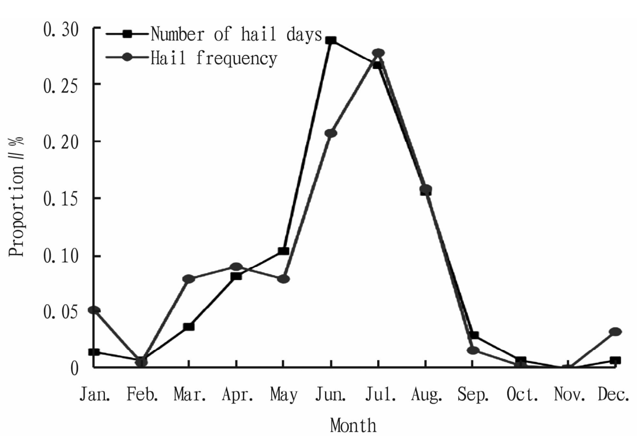

Fig. 2 Proportion of the number of hail days and hail frequency in different months in Qujing City from 2017 to 2022

2.2 Spatial distribution of hail disaster in Qujing City The spatial distribution characteristics of hail frequency in Qujing City in recent 6 years were analyzed. Seen from the total hail frequency in the past 6 years, the hail frequency in Xuanwei was the highest, totaling 80. Qilin District had the lowest hail frequency, only 11. The annual average hail frequency of each street (town) was calculated, and it is found that hail disaster occurred most frequently in the west of Xuanwei, the north of Zhanyi and the north of Luping, followed by the middle of Xuanwei, the north-central part of Fuyuan, the middle of Luping, the north of Shizong, and the middle of Luliang.

2.3 Characteristics of hail diameter and duration of hail processes in Qujing City The hail diameter and duration of 318 hail processes in Qujing City from 2017 to 2022 were analyzed. As shown in Fig. 4, the duration was divided into three levels: ≤10, 10–30 and > 30 min. The total number of hail processes with the three levels of duration was 269, 44 and 5, respectively, accounting for 84.6%, 13.8% and 1.6% of the total number. It can be seen that the duration of most hail processes in Qujing City was within 10 min. Among 318 hail processes, 18 hail processes had no data of hail diameter, so the clearly recorded data of hail diameter in the 300 processes were used for analysis. As shown in Fig. 5, the hail diameter of 6 processes was ≥30 mm in Qujing City from 2017 to 2022, of which the hail with a diameter of ≥30 mm occurred twice in 2019, 2021 and 2022. respectively, accounting for only 2.0% of the total frequency. That is, the proportion of the hail process with hail diameter of ≥30 mm was relatively small.

3 Statistics of the number of artificial hail suppression operations in Qujing

The information of artificial hail suppression operations in Qujing, Yunnan Province from 2017 to 2022 was collated and counted, and it is concluded that the number of artificial hail suppression operations in Qujing in summer in recent 6 years decreased first and then increased (Fig. 6). The total number of artificial hail suppression operations in Qujing City in 2017 was 884, and decreased year by year to 669 in 2019. After 2019, the number of the operations began to increase, and the number of the operations in 2022 was 2.3 times that of 2019. Except the law of the number of the operations in Shizong County was not obvious, the number of the operations in other counties (cities and districts) also reduced firstly and then increased. The number of hail suppression operations in Luping, Zhanyi, Xuanwei, Luliang and other areas was large, and the number of the operations in Luliang, Qilin and Fuyuan in 2022 was nearly double that of previous years.

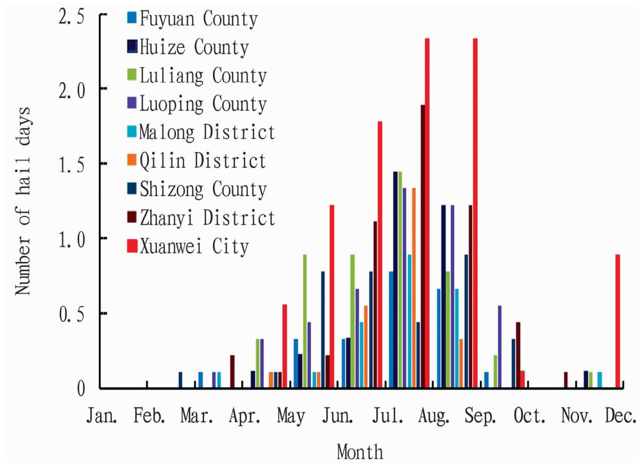

Fig. 3 Monthly distribution of annual average number of hail days in each county (city and district) in Qujing City during 2017 – 2022

4 Analysis of a typical hail suppression process

Based on CINRAD-CA (the new generation of Doppler weather radar) in Qujing City, a typical convective cell case was selected, and combined with the record of artificial hail suppression operations, the effect and efficiency of artificial hail suppression operations were analyzed to provide scientific guidance for regional artificial hail suppression operations.

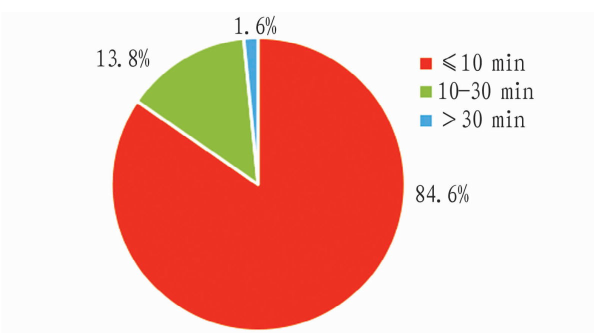

Fig. 4 Distribution of duration of hail processes in Qujing City from 2017 to 2022

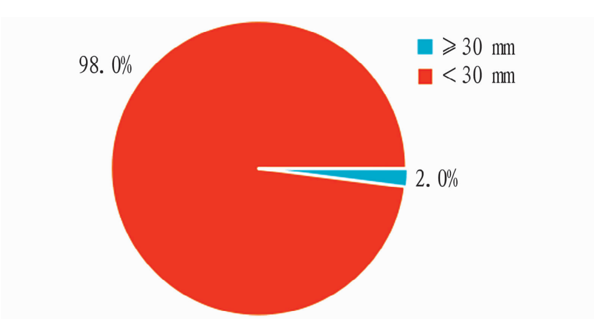

Fig. 5 Distribution of hail diameter in Qujing City from 2017 to 2022

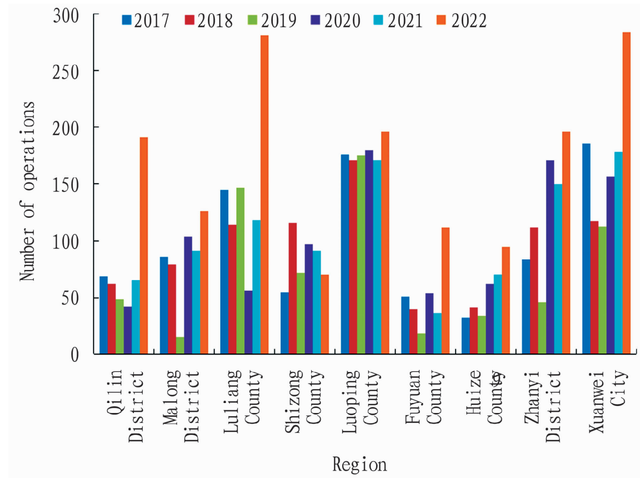

Fig. 6 Number of artificial hail suppression operations in 9 counties (cities and districts) of Qujing City from 2017 to 2022

4.1 Calculation method of operation position The calculation method of the ground operation height is as follows: the longitude and latitude information of the center of hourly strong echo and the operation point, and altitude can be read out from the radar echo combined reflectivity diagram, and can be derived from the operation information reporting system. According to the longitude and latitude of each operation point at each operation time, the horizontal distance L between the operation point and the strong echo center can be calculated by formula (1):

$$L = \sqrt{[(lon_1 - lon_2)^2 + (lat_1 - lat_2)^2] \times 100} \quad (1)$$

According to the altitude, azimuth, elevation angle and horizontal distance of the operation point, the catalytic height of each operation was calculated by formula (2):

$$H = h + Y \quad (2)$$

In the formula, H is the catalytic height of the operation; h is the altitude of the operation point; Y is the vertical height corresponding to different elevation angles. For a strong convection echo, joint operations were carried out at multiple operation points in the same radar detection period, or multiple operations at different elevation angles were carried out at an operation point in a radar body scan range, the operating height can be calculated by the average height, minimum operating height, and maximum operating height. The formulas of minimum operating height H_{min} and maximum operating height H_{max} can be calculated as follows:

$$H_{min} = Tan\ (E_{min}) \times L + h \quad (3)$$

$$H_{max} = Tan\ (E_{max}) \times L + h \quad (4)$$

If operations were carried out at different elevation angles at multiple or one operating point in a radar body scan, the average operating height is calculated as follows:

$$\overline{H} = \frac{\sum H_i}{i} \quad (5)$$

4.2 Weather situation and operation situation

4.2.1 Weather situation. Affected by the development of continental high pressure, the ground convergence line formed over Qilin

District, Qujing City from 14:00 on July 29, 2021, and remained until 20:00 on the same day. With the passage of time, the convergence line gradually shifted from northeast-to-southwest trend to east – west trend, and moved northward from the south of Qilin District to the middle of Zhanyi District. From the altitude field, there was a cold background field over Qilin District at 500 hPa, which was mainly affected by the northerly airflow behind the cold vortex. There was a warm background field at 700 hPa, with unstable stratification, so it was very easy to trigger convection weather.

4.2.2 Operation situation. At 17:29 on the 29th, a multi-cell echo, which was distributed from northwest to southeast and had two strong centers, entered Yunnan Province from the east of Fuyuan County, with a length of 26 and a width of 15 km. At this time, the echo had a certain intensity, and the Qujing Command Center of Artificial Weather Modification notified that the echo moved to the front county or district, and the operation should be prepared. Subsequently, the two strong centers of the echo developed in the process of moving to the south – southwest direction, and a new strong center developed in the northwest, forming three strong centers in parallel.

Table 1 Operation information of ground operation points on July 29, 2021

Operation point	Start time of operation	End time of operation	Strong center height//m	Model number	Number of ammunition used	Operating average height//m	Relatively strong center height//m
Duge	18:19	18:21	5 600	High ammunition (RY-18)	3	5 654	54
Duge	18:31	18:33	6 000	High ammunition (RY-18)	20	5 654	–346
Songlin	18:32	18:34	6 200	High ammunition (RY-18)	23	5 372	–828
Xiaojichang	18:41	18:42	5 100	High ammunition (RY-18)	20	5 061	–39
Duge	18:41	18:43	5 100	High ammunition (RY-18)	19	5 654	554
Xiaojichang	18:42	18:43	5 100	Rocket (9394 Factory BL)	2	5 549	449
Songlin	18:43	18:45	6 800	High ammunition (RY-18)	17	5 372	–1 428
Kouzitou	18:44	18:45	6 800	Rocket (9394 Factory BL)	4	5 489	–1 311
Huangzu	18:44	18:46	6 800	High ammunition (RY-18)	20	5 462	–1338
Samayi	19:52	19:53	4 500	High ammunition (RY-18)	18	4 995	495
Zhuanchanghe	19:53	19:54	4 500	High ammunition (RY-18)	9	5 039	539
Zhuanchanghe	19:56	19:57	5 000	High ammunition (RY-18)	9	5 513	513
Samayi	19:57	19:58	5 000	High ammunition (RY-18)	18	5 469	469
Samayi	20:00	20:01	5 000	High ammunition (RY-18)	18	5 469	469
Zhuanchanghe	20:01	20:02	5 000	High ammunition (RY-18)	9	5 513	513
Hongliangzi	20:06	20:07	5 800	Rocket (9394 Factory BL)	3	5 495	–305
Shitouzhai	20:06	20:07	5 800	High ammunition (RY-18)	18	5 051	–749
Gaoqiao	20:07	20:08	4 500	Rocket (9394 Factory BL)	2	5 452	952
Shitouzhai	20:09	20:10	4 500	High ammunition (RY-18)	18	5 051	551
Hongliangzi	20:10	20:11	4 500	High ammunition (RY-18)	15	5 007	507
Gaoqiao	20:10	20:11	4 500	Rocket (9394 Factory BL)	2	5 452	952
Zhuanchanghe	20:10	20:11	4 500	High ammunition (RY-18)	9	5 513	1 013
Hongliangzi	20:15	20:16	6 200	High ammunition (RY-18)	10	5 007	–1 193
Zhuanchanghe	20:15	20:16	6 200	High ammunition (RY-18)	9	5 039	–1 161
Samayi	20:15	20:16	6 200	High ammunition (RY-18)	18	5 469	–731
Shitouzhai	20:15	20:16	6 200	High ammunition (RY-18)	9	5 051	–1 149
Gewei	20:16	20:17	6 200	High ammunition (RY-18)	10	4 997	–1 203
Gewei	20:18	20:19	6 200	High ammunition (RY-18)	10	4 997	–1 203
Samayi	20:19	20:20	6 100	High ammunition (RY-18)	9	4 995	–1 105
Gangde	20:20	20:22	6 100	Rocket (9394 Factory BL)	2	5 498	–602
Xintaizi	20:20	20:21	6 100	High ammunition (RY-18)	20	5 145	–955
Heimu	20:21	20:22	6 100	High ammunition (RY-18)	30	5 033	–1 067
Gewei	20:22	20:23	6 100	Rocket (9394 Factory BL)	4	6 495	395
Xintaizi	20:26	20:27	5 200	High ammunition (RY-18)	17	5 145	–55
Heimu	20:26	20:27	5 200	High ammunition (RY-18)	30	5 033	–167
Gewei	20:27	20:28	5 200	Rocket (9394 Factory BL)	2	5 485	285
Gewei	20:28	20:29	5 200	High ammunition (RY-18)	10	4 997	–203

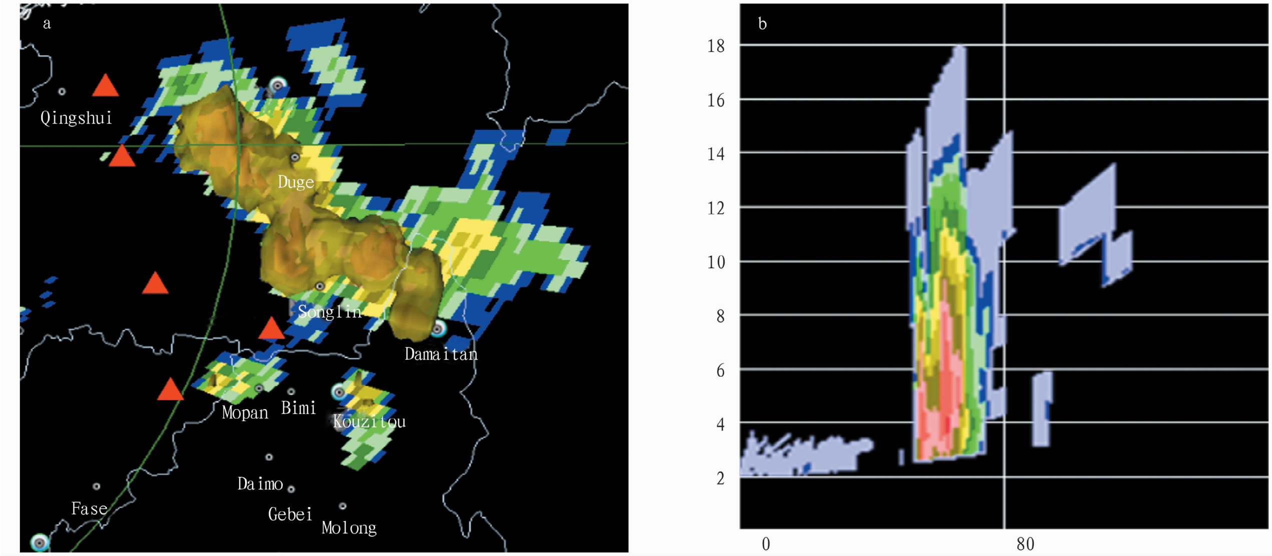

Fig. 7 Superposition diagram of three-dimensional radar of echo A (40 dBz echo is yellow translucent, and 50 dBz echo is red opaque) and operation points (red triangles)(a) and its section direction (b) at 18:31 on July 29

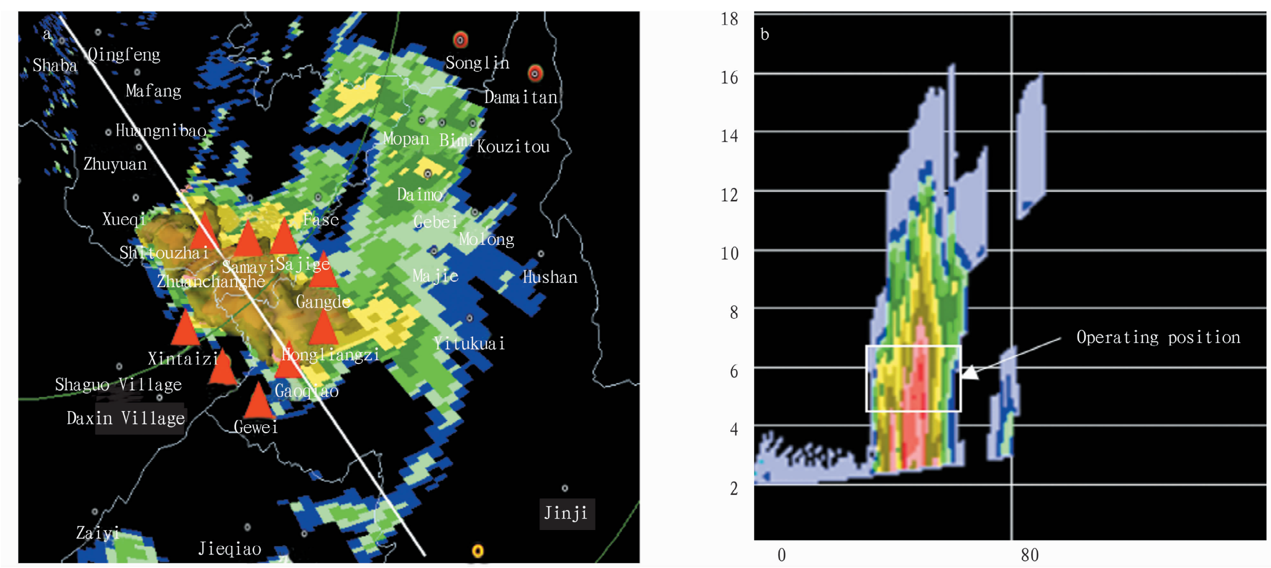

Fig. 8 Superposition diagram of three-dimensional radar of echo A (40 dBz echo is yellow translucent, and 50 dBz echo is red opaque) and operation points (red triangles)(a) and its section direction (b) at 20:12 on July 29

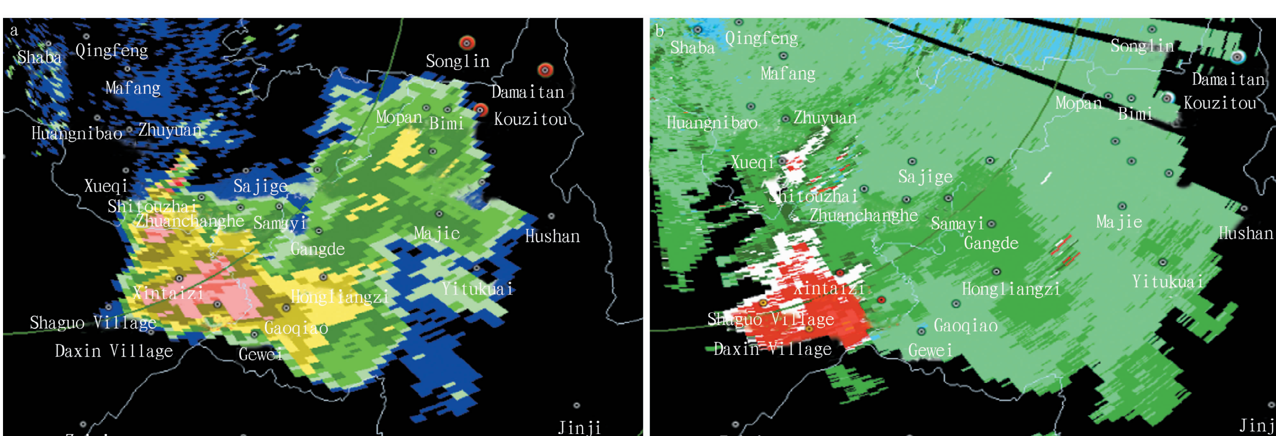

Fig. 9 Echo PPI (a) and velocity map (b) after the operations at 20:29 on July 29

At 18:14, the three strong centers showed a merging trend, and the echo parameters such as the maximum value of VIL (vertically integrated liquid water) increased sharply. At 18:19, the operation started at the Duge operation point below the strong echo center, and the operation position was near the strong centers. The operation position and time were appropriate, but the operation used a small amount of ammunition, and only 3 rounds of RY-18 high ammunition were used, so the operation effect was not good. Through monitoring, it was found that the echoes continued to merge and develop after the operation, and then multi-point joint operations were conducted.

From 18:31 to 18:46, Duge, Songlin and Huangzhu operating points in Fuyuan County and Xiaojichang and Kouzitou operating points in Luoping County successively carried out 8 operations on strong convection echo (Fig. 7), using 119 rounds of high ammunition and 6 rockets. The operation positions were the updraft zones near and under the strong center, and the highest operation position was at 554 m above the strong center, while the lowest operation position was at 1 428 m below the strong center. In the process of operation, the echo was successfully restrained from continuing to develop, and immediately entered the dissipating period, so the operation effect was obvious.

After the operation, the echoes continuously split into several small units in the process of moving to the south – southwest direction, and was distributed regularly from northwest to southeast. It can be seen from the velocity diagram that there was a certain range of wind speed convergence zone in front of the echo, indicating that although the echo weakened, the overall organizational structure and dynamic conditions of the echo had not completely collapsed, and there were conditions for the development again.

At 19:44, a number of small cells formed by the fragmentation of the echo merged, and began to grow for a second time, so that a number of echo parameters increased. From 19:52 to 20:29, at Samayi, Shitouzhai and Zhuanchanghe operating points in Qilin District, Xintaizi and Heimu operating points in Luliang County, and Hongliangzi, Gaoqiao, Gewei and Gangde operating points in Luoping County, 28 operations on strong convection echo were carried out successively (Fig. 8), and 323 rounds of high ammunition and 15 rockets were used. The operation positions were the updraft zones near and under the strong center, and the highest operation position was at 952 m above the strong center, while the lowest operation position was at 1 203 m below the strong center. The operation successfully restrained the echo from continuing to develop, and it immediately entered the dissipating period, so the effect was obvious.

At 20:29, the echo intensity and velocity map (Fig. 9) show that echo intensity and other radar echo parameters had shown obvious dissipation characteristics, and the low-level wind field was divergent. It indicates that the strong echo was disintegrating and dissipating, and it was no longer necessary to carry out operations.

The operation information of each operation point in this process is shown in Table 1.

5 Conclusions and discussion

Qujing is the area with the most frequent hail disaster in Yunnan, among which Xuanwei city has the most frequent hail disaster. From 2017 to 2022, the severe convection weather hail in Qujing City showed a significant increasing trend, and the corresponding number of artificial hail suppression operations also increased. Through the analysis of hail suppression operations of a typical cell case, the overall effect of operation was better. The operation was conducted in the echo merging development stage, and it was timely. The operation positions were in the updraft area near and under the strong center, and they were reasonable. The ammunition used was sufficient, and obviously suppressed and disintegrated the strong convective echo.

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