Predictability and Consideration of Meteorological Service Decision of Extreme Precipitation During May 11 – 16, 2022 in Dehong Prefecture

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Abstract Based on conventional meteorological observation data, radar data and numerical forecast product data, the causes of the first large-scale, high-intensity and long-duration rainstorm in Dehong Prefecture during May 11 – 16, 2022 were analyzed by using the weather dynamic diagnosis and analysis method. The results show that the rainstorm process was caused by strong uplift and condensation in the west and north of Yingjiang under the background of dry and cold northwest air circulation at 500 hPa, the absence of obvious influence of the south branch trough at 700 hPa, and strong southwest jet at 850 hPa. The southwest jet in the boundary layer provided sufficient warm water vapor, unstable energy and uplifting conditions for the rainstorm. Low-level convergence, high-level divergence and strong upward movement in the whole layer were conducive to the uplift and condensation of a large number of warm and humid air in the northwest of Yingjiang in Dehong Prefecture, which enhanced the development of mesoscale convective system (MCS) and prolonged the life history of β mesoscale convective system. The application of satellite, radar and other mesoscale data has an important reference value for the tracking, correction, forecast and early warning of the rainstorm process.

Key words Southwest airflow; Low-level jet; Warm-sector rainstorm; Dehong

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The concept of warm-sector rainstorms originated from the research on warm-sector rainstorms in South China. Generally, they usually occur in the warm zone on the south side of the ground front, or when there is no frontal surface from the Nanling Mountain to the north of the South China Sea, and South China is not affected by cold air or is controlled by a stable cold high-pressure ridge[1]. Sometimes they appear in the convergence airflow between the southwest and southeast airflow and even in the southwest airflow without shear[2]. Warm-sector rainstorms under a weak synoptic scale background are generated under the weather conditions when there are no obvious trough lines at high altitudes or no significant shear effects at the middle and lower layers. Such warm-sector rainstorms have unclear triggering mechanisms, poor numerical forecasting capability, and high forecasting difficulty, and thus have greater research value[3]. Warm-sector rainstorms under a weak synoptic scale background can be classified as strong southwest jet type and subtropical high type[3]. The first type of warm-sector rainstorms mainly occur in spring, and can occur at any time of the day, with an increase in the frequency of nocturnal precipitation. A low-level jet is considered an important weather process that provides thermodynamic and dynamic conditions for mid-latitude rainstorms and strong storms. Some studies have pointed out that the correlation between low-level jet and rainstorms is very strong. In the plum rain period of the Jianghuai region, low-level jets appeared in 70% of the days, and 79% of the low-level jets were accompanied by rainstorms, while 83% of the rainstorms were accompanied by low-level jets[4]. The existence of low-level southwest jets is conducive to the development of mid-scale disturbances into low vortices, so that strong convective development triggers the release of latent heat, resulting in rainstorms[5]. There is a positive feedback effect between low-level jets and rainstorms, and rainstorms usually occur in the left front of the center of low-level jets[6]. Therefore, a low-level jet is one of the important systems conducive to the formation of warm-sector rainstorms.

Dehong Dai and Jingpo Autonomous Prefecture (97°31′ – 98°43′ E, 23°50′ to 25°20′ N) is located in the southwestern border area of China, in the west of Yunnan Province and on the border with Myanmar, with the total area of 11 526 km^2[7]. There are few observation stations in the western upstream area adjacent to Myanmar, which brings great difficulty to weather forecast[8]. Dehong is located in the west of the Yunnan – Guizhou Plateau and the south of the Xiangjiang Mountains, and to the west of the Gaoligong Mountain. It is high and steep in the northeast and low and gentle in the southwest. It is in the windward slope area at the northeastern end of the low-altitude trumpet-shaped terrain area in the central-western part of Myanmar that is uplifted towards the west of Yunnan Province. The topographical conditions are extremely conducive to the development of precipitation clouds, are prone to form local short-term heavy precipitation, and may also lead to secondary geological disasters such as landslides, mud-

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slides and mountain floods[9]. Therefore, research on rainstorms in Dehong is very important for disaster prevention and mitigation.

To sum up, warm-sector rainstorms have always been a difficult point in the forecast of rainstorms during the pre-flood season in South China, and the trumpet-shaped terrain in the northeast of Guangxi has a significant effect on the increase of precipitation, making the forecast of warm-sector rainstorms in this area more difficult[10]. Similarly, the extreme heavy precipitation process in Dehong Prefecture (with a trumpet-shaped terrain) from May 11 to 16 in 2022, was also a warm-sector rainstorm process caused by strong southwest airflow. In this paper, under the weak upper-level weather situation, the mesoscale characteristics and weather-scale environmental characteristics of this rainstorm process were analyzed based on conventional meteorological observation data, radar data and numerical forecast product data, and the focus of forecasting for this type of warm-sector rainstorms in a weak weather-scale background was sought to make more accurate forecast and provide reference for disaster prevention and mitigation.

1 Actual conditions, disaster situation and social impact

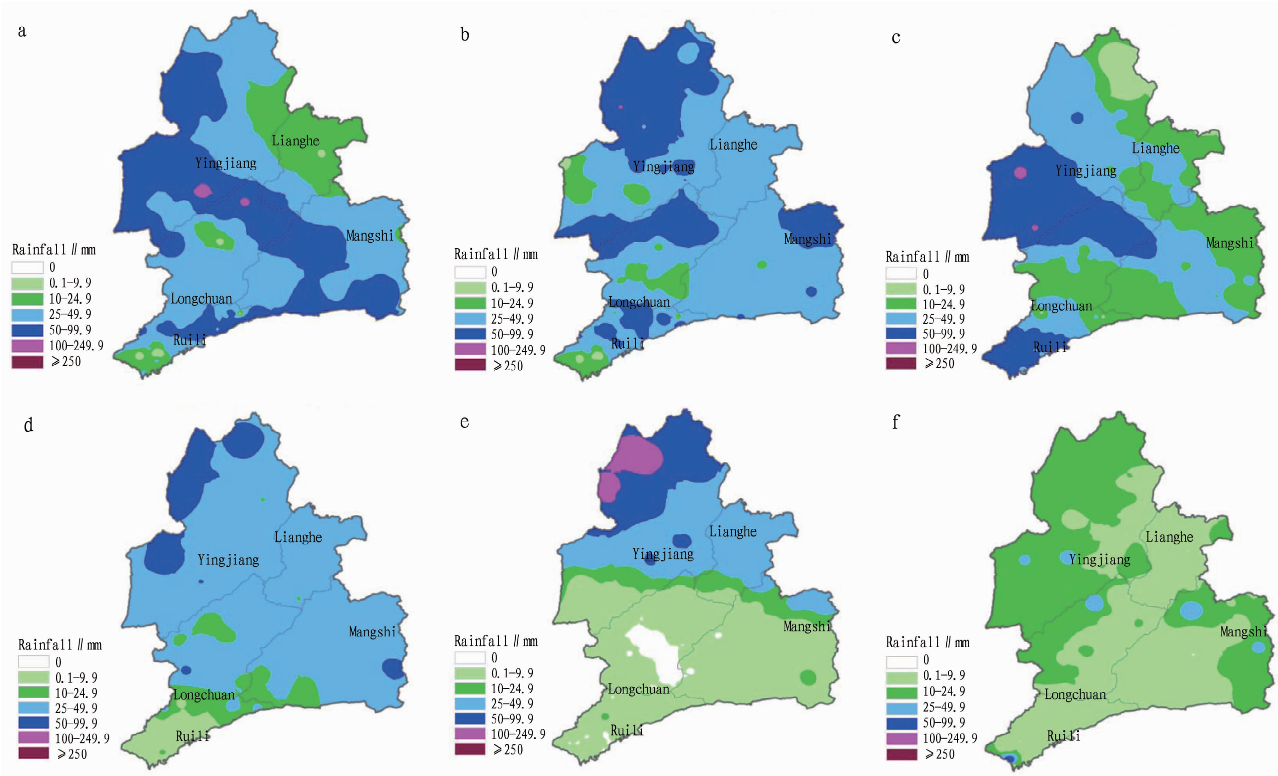
1.1 Actual conditions and precipitation characteristics From May 11 to 16 in 2022, Dehong Prefecture experienced the first rainstorm weather process with high precipitation intensity, wide impact area and long duration due to the impact of the southwest airflow from the periphery of the Bay of Bengal. The entire prefecture suffered from mostly moderate to heavy rain and locally rainstorms and heavy rainstorms. The strongest rainfall happened on May 11, 12 13 and 15. Heavy rainstorm occurred at 1 – 2 township stations. Specific data can be found in Table 1. The spatial distribution of daily rainfall from May 11 to 16 in 2022 is shown in Fig. 1, and the spatial distribution of cumulative rainfall is shown in Fig. 2.

From 20:00 on May 10 to 20:00 on May 16, the average cumulative rainfall at 119 regional monitoring stations in the entire prefecture was 173.1 mm. Cumulative rainfall was ≥250 mm at 10 stations (accounting for 8.4%), 100 – 249.9 mm at 96 stations (80.7%), 50 – 99.9 mm at 8 stations (6.7%), and < 50 m at 1 station (0.8%). The top three stations with the largest cumulative rainfall during the process were Sudian (370.2 mm), Mengdian River (366.4 mm), and Kachang (364.4 mm) in Yingjiang County. From May 11 to 16, there were heavy rainstorms at 7 stations, rainstorms at 118 stations, and heavy rain at 237 stations.

Table 1 Number of stations with different levels of 24-hour rainfall and maximum daily rainfall in the entire prefecture from 20:00 on May 10 to 20:00 on May 16 in 2022

Date	Graded rainfall (number of stations)	Maximum daily rainfall (regional station)//mm	Maximum daily rainfall (county-level monitoring station)//mm	Main areas of rainstorms
May 11	Heavy rainstorm (2 stations), rainstorm (32 stations), heavy rain (55 stations), moderate rain (20 stations) and light rain (3 stations)	125.3 (Nongzhang, Yingjiang County)	57.2 (Yingjiang)	The northwest of Yingjiang, the north of Longchuan, and the center of Mangshi
May 12	Heavy rainstorm (1 station), rainstorm (33 stations), heavy rain (57 stations), moderate rain (19 stations) and light rain (3 stations)	102.3 (Kachang, Yingjiang County)	55.5 (Longchuan)	The north of Yingjiang, the north of Longchuan, and the east of Mangshi
May 13	Heavy rainstorm (2 stations), rainstorm (36 stations), heavy rain (34 stations), moderate rain (37 stations) and light rain (6 stations)	107.5 (Mangxian Village, Yingjiang County)	70.5 (Ruili)	The northwest of Yingjiang, the north of Longchuan, and the southwest of Ruili
May 14	Rainstorm (7 stations), heavy rain (63 stations), moderate rain (16 stations) and light rain (29 stations)	71.6 (Lushan, Yingjiang County)	43.5 (Mangshi)	The northwest of Yingjiang
May 15	Heavy rainstorm (2 stations), rainstorm (9 stations), heavy rain (23 stations), moderate rain (5 stations) and light rain (54 stations)	124.9 (Sudian, Yingjiang County)	64.5 (Yingjiang)	The northwest of Yingjiang
May 16	Rainstorm (1 station), heavy rain (5 stations), moderate rain (29 stations) and light rain (70 stations)	93.3 (Nature Conservation Institute in Ruili)	9.4 (Longchuan)	The south of Ruili
Maximum	Heavy rainstorm (7 stations), rainstorm (118 stations), and heavy rain (237 stations)	125.3 (Sudian, Yingjiang County)	70.5 (Ruili)	The northwest of Yingjiang, and the north of Longchuan

1.2 Disaster situation and social impact During this heavy rainfall process, floods, landslides and mudslides occurred in five counties and cities across the entire prefecture. The disaster situation in Mangshi mainly appeared from May 12 to 16, so that 1 011 people were affected, and the direct economic loss reached 1.527 3 million yuan. The disaster situation in Ruili mainly occurred from May 12 to 13, causing 497 people to be affected and resulting in a direct economic loss of 1.527 3 million yuan. In Longchuan, the disaster situation mainly appeared from May 12 to 16, causing 9 433 people to be affected and leading in a direct economic loss



Note: a. From 20:00 on May 10 to 20:00 on May 11; b. From 20:00 on May 11 to 20:00 on May 12; c. From 20:00 on May 12 to 20:00 on May 13; d. From 20:00 on May 13 to 20:00 on May 14; e. From 20:00 on May 14 to 20:00 on May 15; f. From 20:00 on May 15 to 20:00 on May 16.

Fig. 1 Spatial distribution of rainfall in Dehong Prefecture from May 11 to 16 in 2022

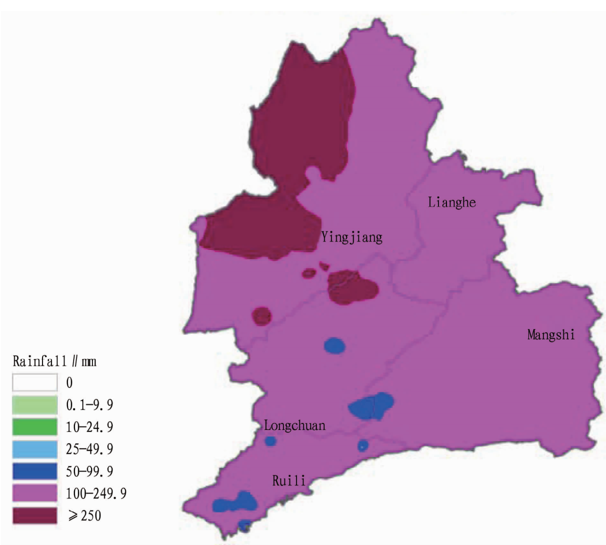


Fig. 2 Spatial distribution of cumulative rainfall in Dehong Prefecture from May 11 to 16 in 2022

of 5.081 million yuan. The disaster situation in Lianghe mainly occurred from May 12 to 18, so that 5 516 people were influenced, and the direct economic loss was up to 10.959 1 million yuan. In Yingjiang, the disaster situation mainly happened from May 12 to 15, so that 6 township farms and 13 128 people of 3 350 households were affected, leading to a direct economic loss of 14.394 6 million yuan. The statistics of the disaster situation are shown in Table 2.

2 Forecast and service situation, forecast verification and forecast challenges

2.1 Forecast and service situation

2.1.1 Forecast and services.

2.1.1.1 Decision-making meteorological services. On the afternoon of May 11, Dehong Prefecture Meteorological Observatory produced and released the first issue of *Important Weather Forecast*. From May 11 to 16, a total of 9 issues of the *Actual Situation of Rainfall Weather* and 5 issues of *Important Weather Bulletin* were produced and released.

2.1.1.2 Release of warning information. From May 11 to 16, a total of 6 rainstorm warnings were issued, with a total of 2 169 people receiving the warnings. Among them, 3 yellow warnings were issued, with 1 164 people receiving the warnings; 3 blue warnings were issued, with 1 170 people receiving the warnings.

2.1.1.3 Release of risk warnings. From May 11 to 16, 5 geological disaster risk warnings were issued in collaboration with the natural resources department, with a total of 2 060 people receiving the warnings; in collaboration with the hydrological department, 5 mountain flood disaster warnings were issued, with a total of 1 920 people receiving the warnings.

2.1.1.4 "Internal response, and external coordination" service.

On May 11, after the Dehong Prefecture Meteorological Observatory issued a yellow rainstorm warning, the Dehong Flood Control and Drought Relief Headquarters promptly issued an urgent notice for preventing mountain floods and geological disasters based on the yellow rainstorm warning information. During May 11 – 16, telephone alert services were provided to the Dehong Emergency Management Bureau, Dehong Water Resources Bureau, and Natural Resources Bureau 18 times. The issued rainstorm warnings, geological disaster warnings, and mountain flood warnings were released not only through the Yunnan Warning Release Center but also through the Dehong Emergency Broadcasting Platform.

Table 2 Disaster situation of the heavy Rainfall Process in Dehong Prefecture from May 12 to 16 in 2022

Region	Basic loss						Agricultural loss						
	Number of affected people	Number of deaths	Number of missing people	Number of injured people	Number of emergency transfer people	Number of damaged houses	Area of affected crops//hm^2	Area with no harvest hm^2	Direct economic loss 10^4 yuan	Agricultural loss 10^4 yuan	Infrastructure loss 10^4 yuan	Loss of houses and household property 10^4 yuan	Other loss 10^4 yuan
Mangshi	1 011	–	–	–	–	–	45.20	6.60	152.73	98.25	–	–	54.48
Ruili	497	–	–	–	–	–	27.09	–	36.93	29.42	6	1.51	–
Longchuan	9 433	–	–	–	–	40	139.87	–	508.10	421.60	–	–	86.60
Yingjiang	13 128	–	–	–	–	–	663.59	50.07	1 439.46	1 288.46	151	–	–
Lianghe	5 516	–	–	–	5	6	388.55	8.04	1 095.91	1 019.31	62	8.60	6.00
Total	29 585	0	0	0	5	46	1 264.30	64.71	3 233.13	2 857.04	219	10.11	147.08

2.1.2 Service effect.

2.1.2.1 Decision-making service effect. During this heavy precipitation weather process, the Dehong Prefecture Meteorological Observatory issued the Important Weather Forecast 12 hours in advance, and reported it to all local governments and various departments of the flood control and disaster reduction committee through electronic documents and mobile decision-making groups. The Dehong Flood Control and Drought Relief Headquarters issued an urgent notice for the prevention and response to heavy rainfall based on the Important Weather Forecast. The forecast of the heavy precipitation process was consistent with the actual situation, and the service effect was good.

2.1.2.2 Effect of weather warnings. At 08:00 on May 12, an elementary report on the disaster situation from Mangshi Meteorological Bureau was received. 1 011 people were affected, and the direct economic loss was 1.527 3 million yuan.

(1) Verification of the effect of warning information release. At 17:00 on May 11, the Dehong Prefecture Meteorological Observatory issued a yellow rainstorm warning. The yellow rainstorm warning was issued 15 h before the disaster occurred.

(2) Verification of the effect of risk warnings of geological disasters and mountain flood disasters. At 22:00 on May 11, the Dehong Prefecture Meteorological Observatory jointly issued a geological disaster risk warning with the Dehong Natural Resources Bureau, and the risk warning was issued 10 hours before the disaster occurred. At 09:40 on May 12, it jointly issued a mountain flood disaster warning with the Dehong Hydrological Bureau, and the risk warning was issued 10 h before the disaster appeared. The issued warnings about rainstorms, geological disasters, and mountain floods were released not only by the Yunnan Warning Release Center but also by broadcasted promptly through the Dehong Emergency Broadcasting Platform, so that the society is widely aware of them.

All levels of government and departments strengthened disaster prevention and hazard investigation in key areas, took timely preventive measures, and minimized casualties to the greatest extent. The meteorological department fully played its role as the "first line of defense for disaster prevention and mitigation".

2.1.2.3 Effect of public services. From May 11 to 16, warning information and weather real-time information were timely released to the public through mobile text messages, television, WeChat official accounts, and email. The number of mobile text message services reached 24, with a total of 7 409 people receiving the services. Weather and risk warnings were continuously broadcast on the traffic and tourism radio station for 19 times. Meteorological information was released 7 times through the WeChat public platform. Meteorological information was released 7 times through the WeChat public platform. In addition, public media such as Dehong TV, traffic and tourism radio, WeChat, and websites widely forwarded the heavy rainfall weather process and disaster situation. The public widely knew the important weather forecast and warning information released.

2.2 Evaluation of objective and subjective forecast verification

2.2.1 Spatial verification of daily precipitation. The spatial verification of precipitation conditions and prediction results based on various models in Dehong Prefecture from May 11 to 16 are shown in Fig. 3 – Fig. 8. On May 11, the prediction values were smaller than the actual values, and the falling areas of heavy rain were predicted better based on CMA-GFS, while the falling areas of rainstorms was predicted better based on CMA-SH9. However, the falling areas of rainstorms were smaller, and the actual areas were larger. On May 12, the prediction values were also smaller than the actual values, and the prediction effect of falling areas of heavy rain and rainstorms based on CMA-GD was better, but the falling areas of rainstorms were still smaller. On May 13, the prediction values were also smaller than the actual values, and the prediction effect of falling areas of heavy rain and rainstorms based on SPCC was better, but the falling areas of rainstorms were still smaller than the actual areas. On May 14, the prediction values were smaller than the actual values, and the prediction effect of falling areas of heavy rain and rainstorms based on the research institute WRF was better, but the falling areas of rainstorms were still smaller. On May 15, the prediction values were smaller than the actual values, and the falling areas of heavy rain and rainstorms were predicted better based on CMA-GD, while the falling areas of rainstorms were still smaller, and the falling areas of heavy rainstorms were not shown. On May 16, the prediction effect of falling areas of heavy rain and rainstorms based on the research institute WRF was better. In fact, the predicted falling areas of rainstorms did not appear, and only heavy rain happened.

2.2.2 Temporal verification of precipitation. The temporal verification of the TS score of rainstorms in Dehong Prefecture from May 11 to 16 is shown in Fig. 9 and Table 3. A total of 9 models were used in this verification. Among them, the model with the highest TS score was CMA-MESO (0.21) on May 11, SPCC (0.37) on May 12, CMA-GD (0.22) on May 13, and SPCC (0.16) on May 14, respectively. On May 15, TS score was all 0. On May 16, only SCMOC, SPCC and YNKG were adopted, and their TS score was all 0.

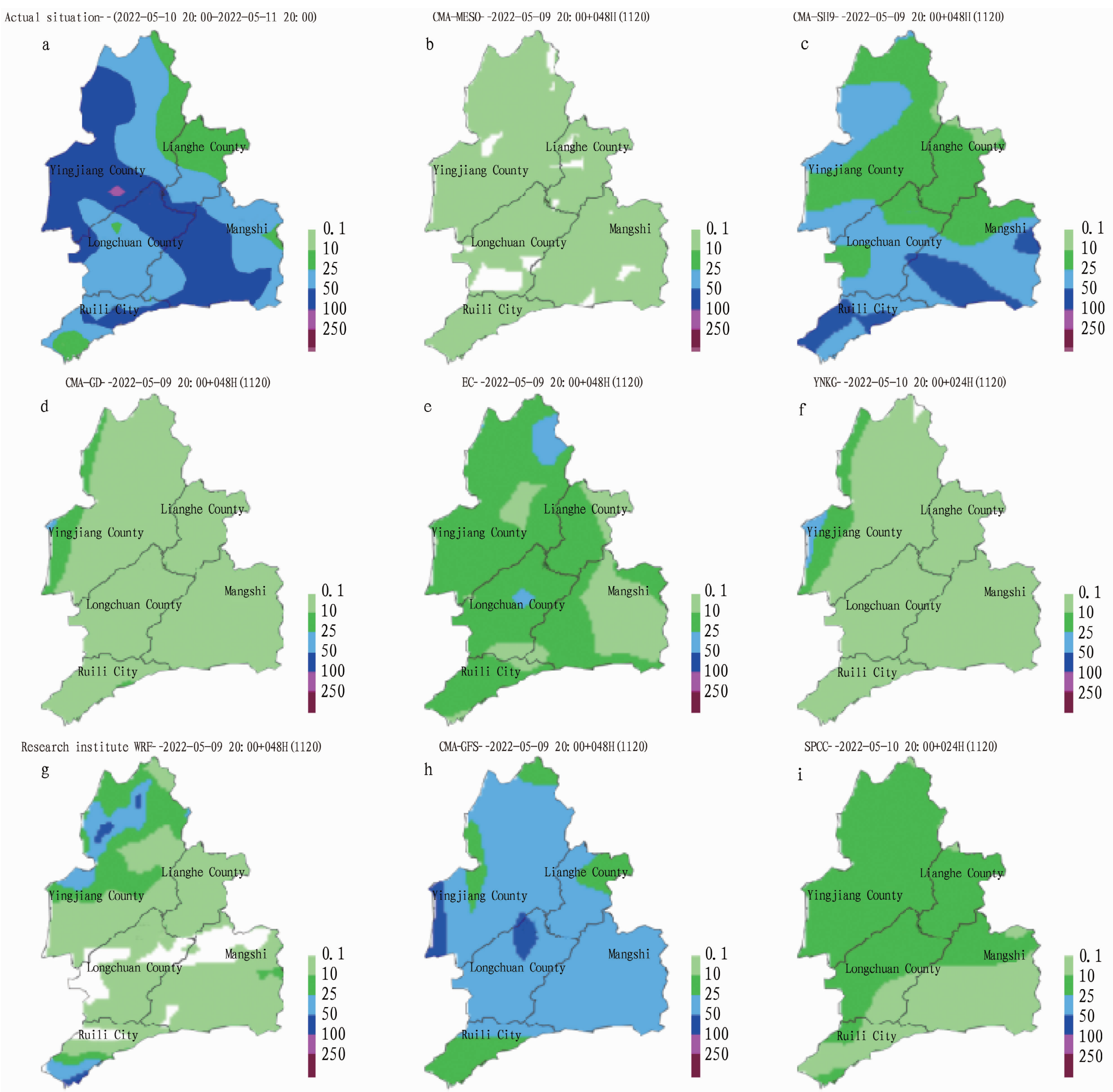


Fig. 3 Actual and prediction results of precipitation in Dehong Prefecture from 20:00 on May 10 to 20:00 on May 11 in 2022

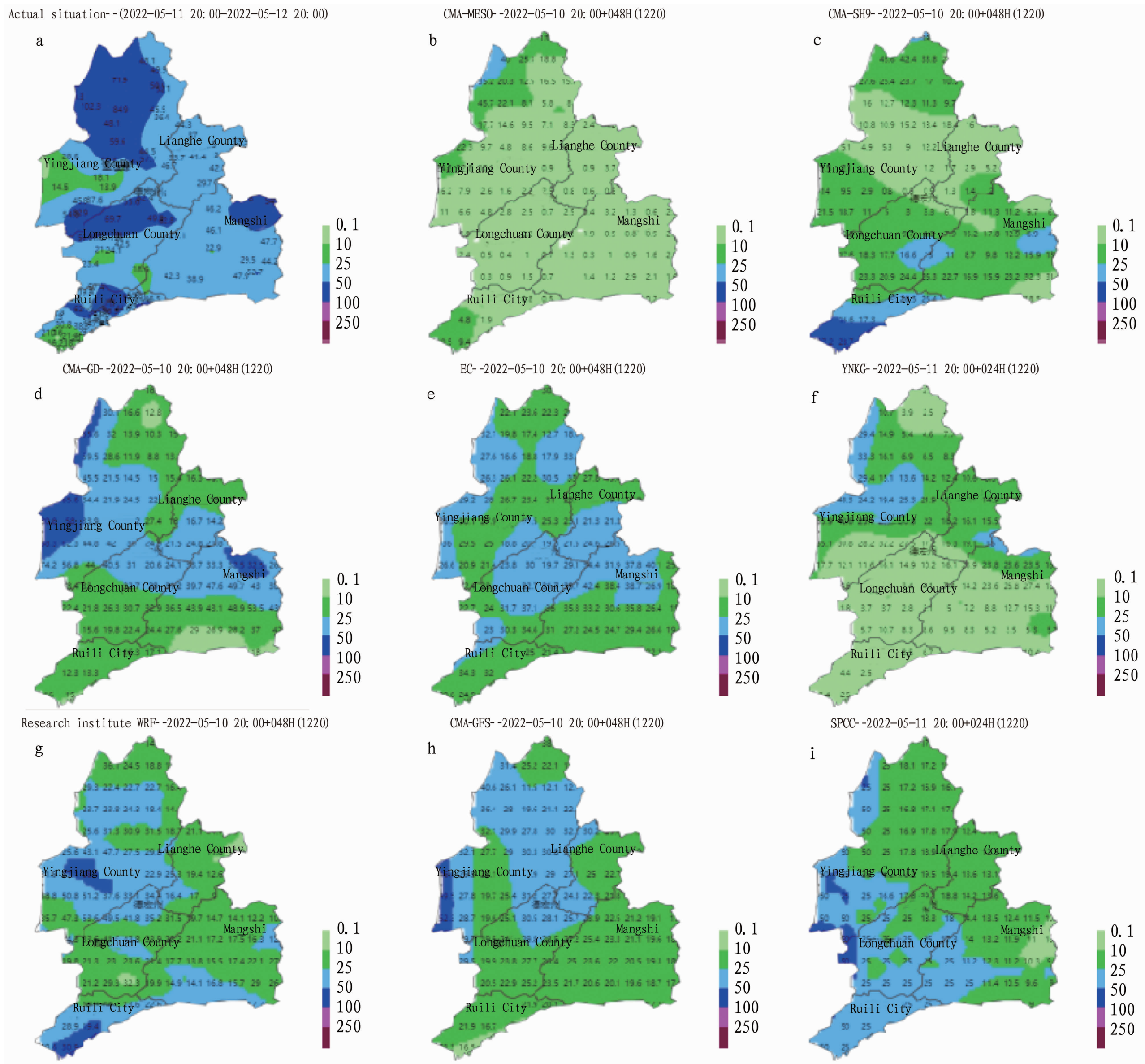


Fig. 4 Actual and prediction results of precipitation in Dehong Prefecture from 20:00 on May 11 to 20:00 on May 12 in 2022

Table 3 TS score of rainstorms in Dehong Prefecture from May 11 to 16 in 2022

Model	Date (primary/secondary)					
	05-11 (24/48)	05-12 (24/48)	05-13 (24/48)	05-14 (24/48)	05-15 (24/48)	05-16 (24/48)
SCMOC	0	0	0	0	0	0
SPCC	0.09	0.37	0	0.16	0	0
DMS	–	–	–	–	–	–
YNKG	0	0	0.13	0	0	0
Research institute WRF	0	0.09	0.14	0	0	–
CMA-GFS	0	0	0	0	0	–
CMA-MESO	0.21	0	0	0	0	–
CMA-SH9	0	0.13	0	0	0	–
CMA-GD	0	0.29	0.22	0	0	–
EC	0	0	0	0	0	–
Southwest	–	–	–	–	–	–

The model forecast error of cumulative precipitation in Dehong Prefecture from May 11 to 16 is shown in Fig. 10. The number of used models was 10. The actual value was 764.20 mm. Among them, the forecast values based on YNKG and EC were relatively close to the actual value, namely 815.38 and 795.73 mm, respectively.

2.3 Analysis of forecast difficulties

2.3.1 Forecast situation. After the fact that light to moderate rain appeared in most areas and heavy rain happened locally on May 10, the future intensity of rainfall on May 11 would be stronger than that on May 10, so the predicted rainfall from May 11 to 16 was adjusted to moderate to heavy rain with local rainstorms. On May 11, an important weather forecast was issued. Affected by the southwest airflow, a heavy rainfall process would occur in Dehong from May 12 to 16. The cumulative rainfall during this

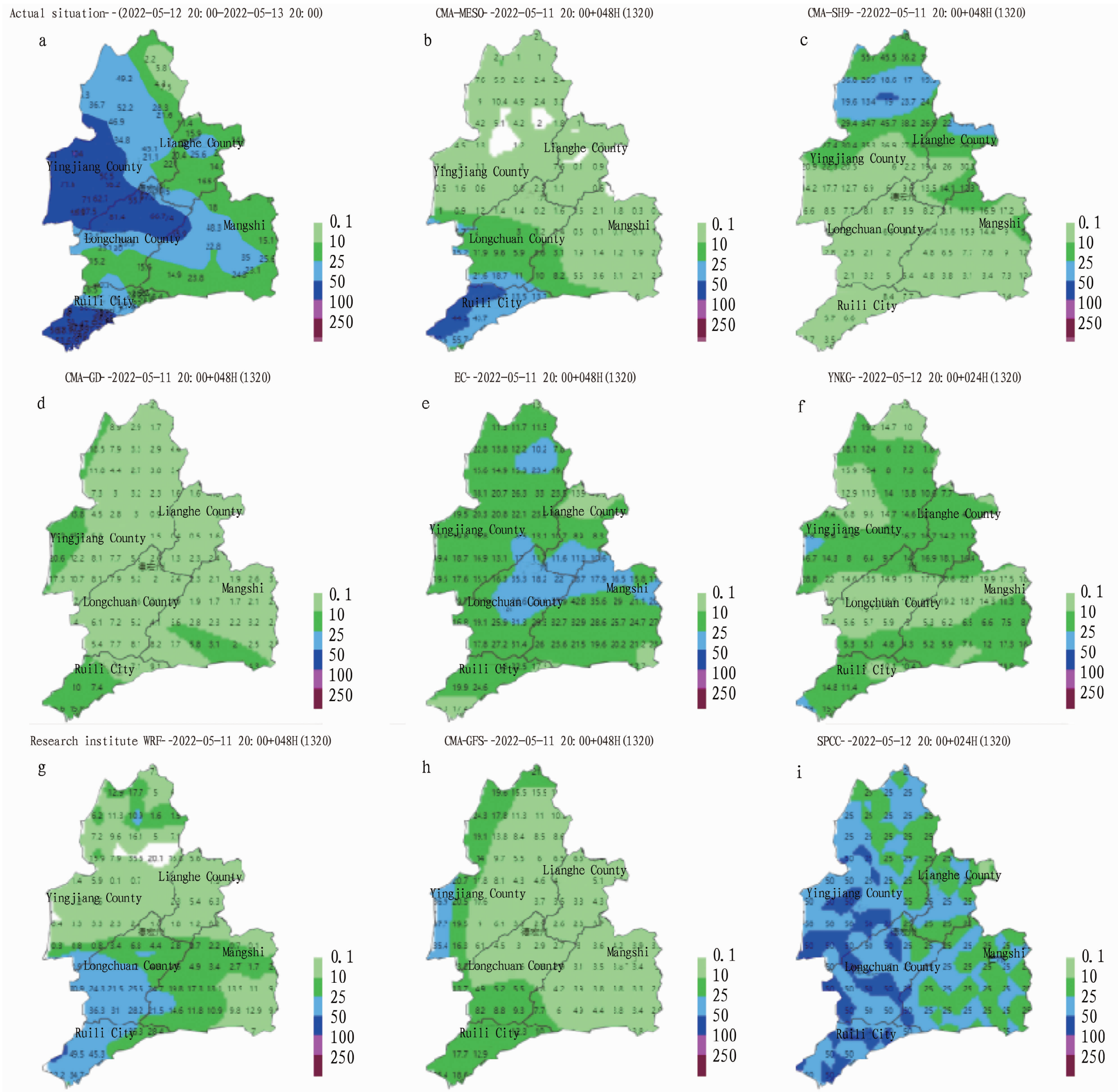


Fig. 5 Actual and prediction results of precipitation in Dehong Prefecture from 20:00 on May 12 to 20:00 on May 13 in 2022

process would be mostly 60 – 100 mm in most areas and locally 120 – 180 mm. The specific forecast situation is as follows: there would be moderate to heavy rain with local severe rainstorms on May 12, moderate rain with local heavy rain on May 13, and moderate to heavy rain with local severe rainstorms from May 14 to 16. During the rainfall process, strong convective weather such as thunderstorms, strong winds, hail, and short-term heavy precipitation might happen in local areas, it is needed to pay attention to prevention. The specific forecast situation is shown in Table 4.

2.3.2 Comparison between prediction and actual conditions. On May 11, 12, 13, and 15, heavy to torrential rain with local heavy rainstorms appeared, while the predicted level of precipitation was lower, and the falling area of heavy rainstorms was not accurately predicted. On May 14, the forecast was accurate, that is, there would be moderate to heavy rain and local rainstorms. On May 16, the predicted level of precipitation was higher, that is, there would be moderate to heavy rain and local rainstorms. In fact, light to moderate rain with local heavy rain happened, and there were no rainstorms.

Forecast difficulties are as follows. There was no obvious southward trough at 500 and 700 hPa on the upper air maps. At 850 hPa, there was a southwest jet, and Dehong Prefecture was located at the exit of the southwest jet. That is, when there are significant differences in the predicted falling areas of rainstorms and above based on various models under a weak weather background, the prediction of falling areas of rainstorms and heavy rainstorms has become a major difficulty. In the quantitative forecast of heavy rainfall, the intensity and the duration of rainfall are the difficulties and key points of the forecast.

3 Analysis of causes of heavy rainfall and forecast deviation (including predictability analysis)

3.1 Circulation pattern and development and evolution of main weather systems The distribution of flow fields at 500 hPa in Dehong Prefecture at 08:00 on May 11 to 16 in 2022 is shown in Fig. 11. On May 11, under the control of the northwesterly airflow and westerly airflow from the periphery of the Bay of Bengal, there was a stream of westerly airflow in Dehong, and wind speed reached 12 m/s. On May 12, it was still controlled by two streams of airflow, and westerly airflow from the periphery of the Bay of Bengal was slightly weaker than that on May 11, with a wind speed of 12 – 14 m/s. From May 13 to 14, it was mainly controlled by northwesterly airflow, and wind speed increased from 8 – 12 m/s on May 13 to 16 m/s on May 14. On May 15, it was mainly controlled by northwesterly airflow, and northwesterly airflow weakened, with a wind speed ranging from 8 to 10 m/s. On May 16, westerly airflow weakened further, and wind speed was relatively weak, ranging from 6 to 8 m/s. On May 11, 12 and 14, there was an upper air northwesterly jet.

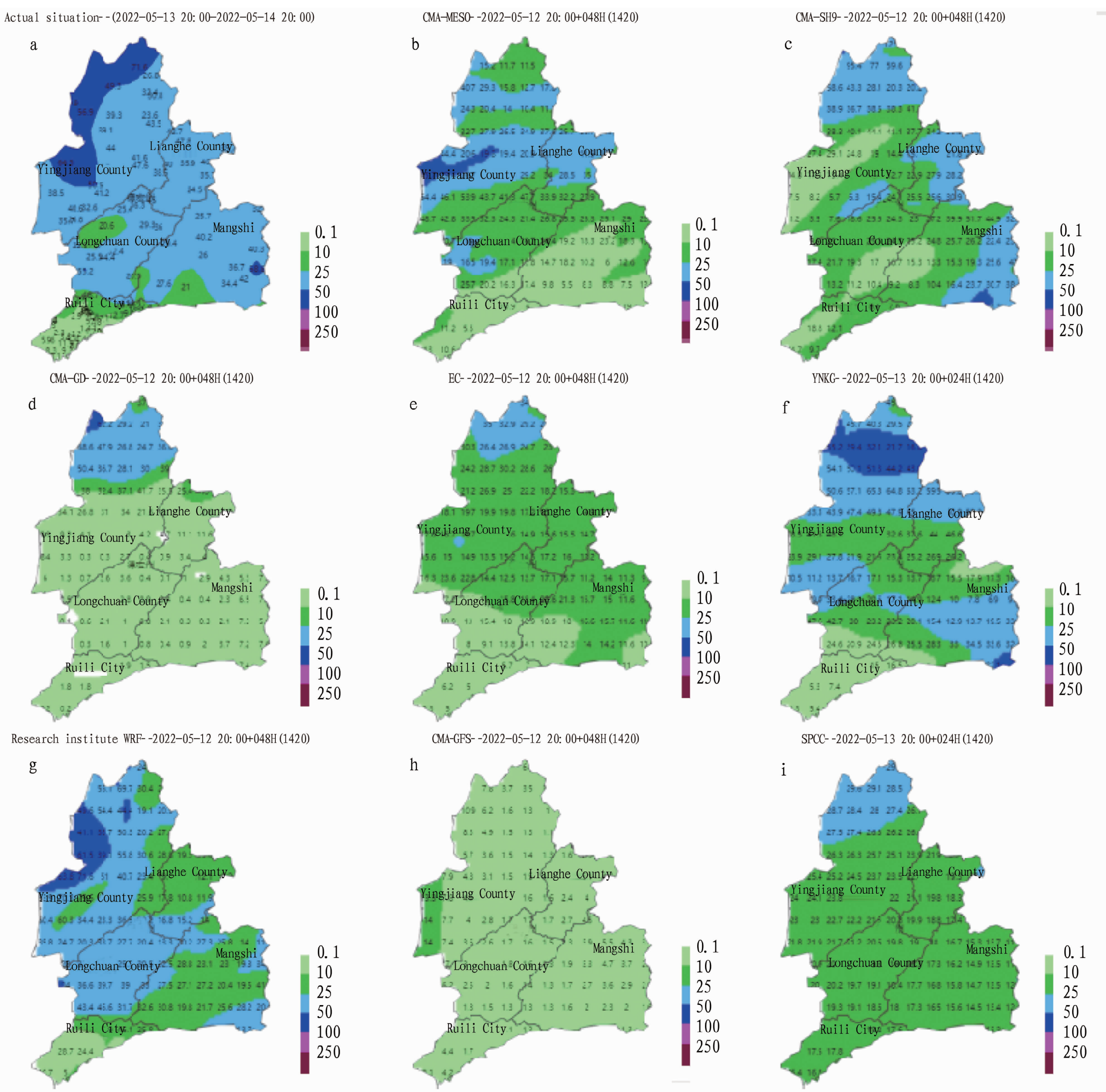


Fig. 6 Actual and prediction results of precipitation in Dehong Prefecture from 20:00 on May 13 to 20:00 on May 14 in 2022

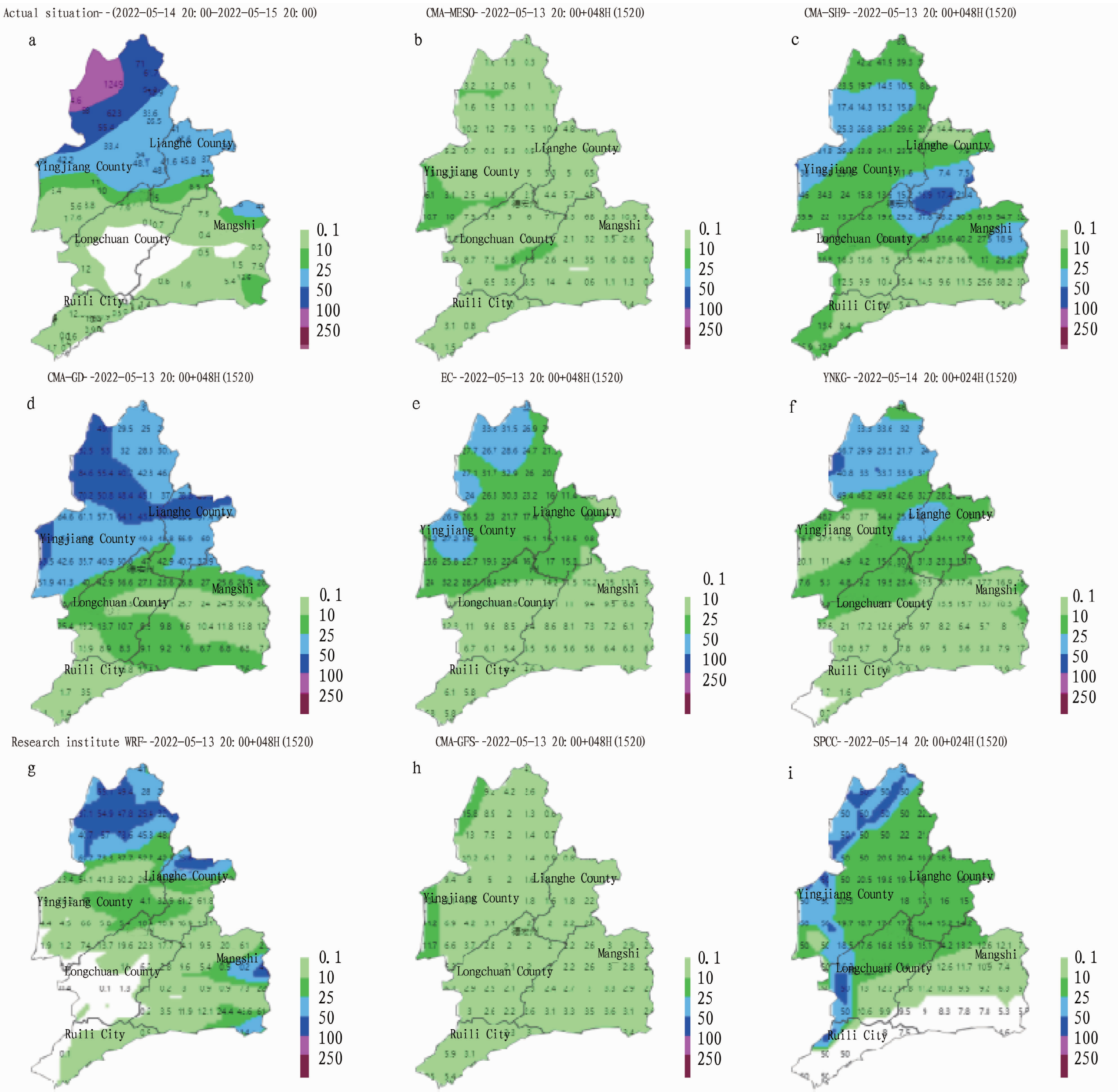


Fig. 7 Actual and prediction results of precipitation in Dehong Prefecture from 20:00 on May 14 to 20:00 on May 15 in 2022

Table 4 Results of the important weather forecast issued by the Dehong Prefecture Meteorological Observatory from May 12 to 16 in 2022

Region	May 12	May 13	May 14	May 15	May 16
Mangshi	Moderate to heavy rain with local rainstorms (21 – 27 ℃)	Moderate rain with heavy rain (21 – 28 ℃)	Moderate to heavy rain with local rainstorms (21 – 28 ℃)	Moderate to heavy rain with local rainstorms (21 – 28 ℃)	Moderate to heavy rain with local rainstorms (21 – 28 ℃)
Ruili	Moderate to heavy rain with local rainstorms (22 – 30 ℃)	Moderate rain with heavy rain (21 – 30 ℃)	Moderate to heavy rain with local rainstorms (22 – 30 ℃)	Moderate to heavy rain (22 – 31 ℃)	Moderate to heavy rain with local rainstorms (21 – 30 ℃)
Longchuan	Moderate to heavy rain with local rainstorms (20 – 28 ℃)	Moderate rain with heavy rain (19 – 28 ℃)	Moderate to heavy rain with local rainstorms (20 – 28 ℃)	Moderate to heavy rain (20 – 28 ℃)	Moderate to heavy rain with local rainstorms (19 – 28 ℃)
Yingjiang	Moderate to heavy rain with local rainstorms (21 – 28 ℃)	Moderate rain with heavy rain (21 – 29 ℃)	Moderate to heavy rain with local rainstorms (22 – 28 ℃)	Moderate rain with heavy rain (20 – 29 ℃)	Moderate to heavy rain with local rainstorms (21 – 29 ℃)
Lianghe	Moderate to heavy rain with local rainstorms (20 – 25 ℃)	Moderate rain with heavy rain (19 – 26 ℃)	Moderate to heavy rain with local rainstorms (19 – 26 ℃)	Moderate to heavy rain with local rainstorms (19 – 25 ℃)	Moderate to heavy rain with local rainstorms (19 – 26 ℃)

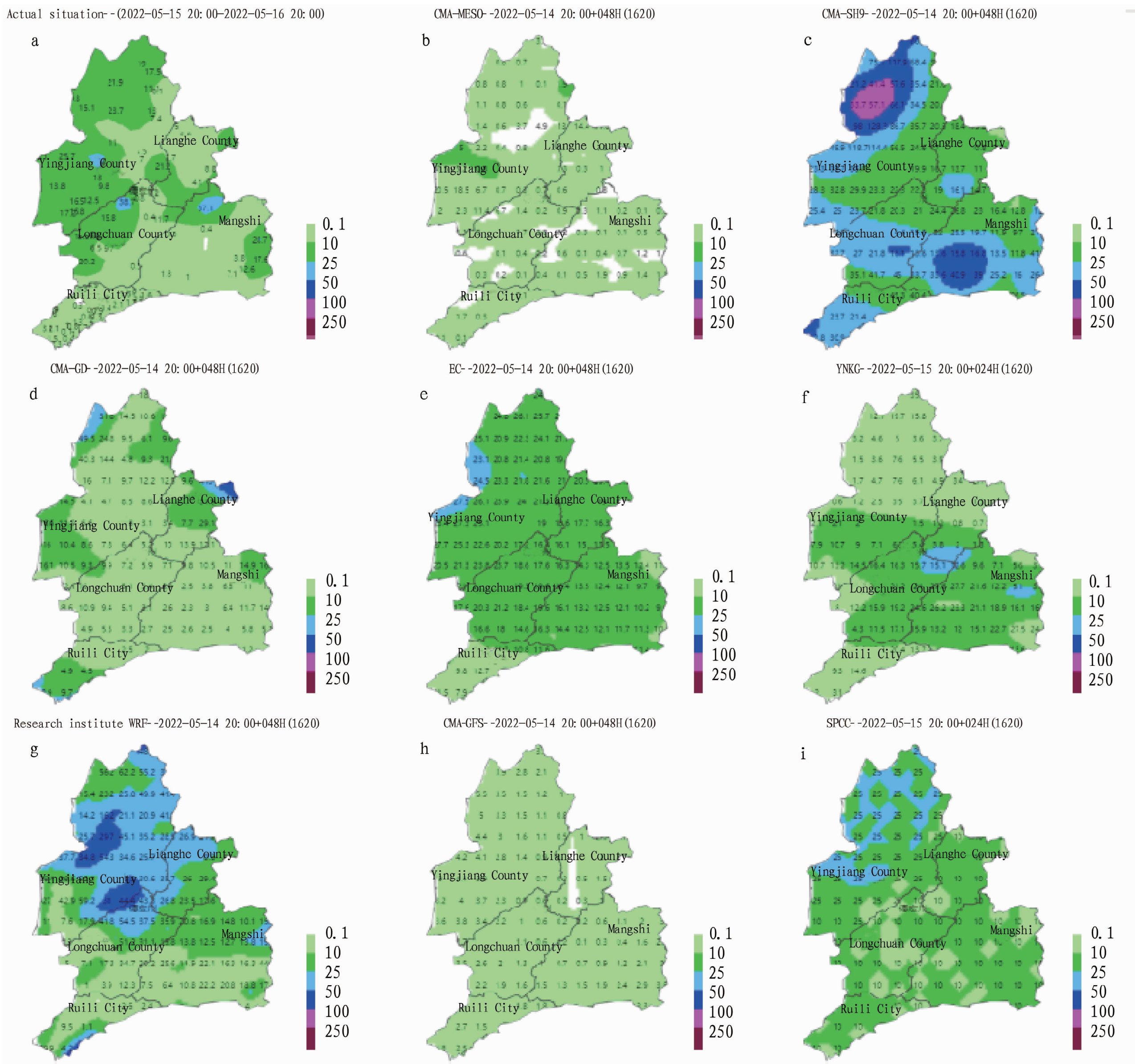


Fig. 8 Actual and prediction results of precipitation in Dehong Prefecture from 20:00 on May 15 to 20:00 on May 16 in 2022

Fig. 12 shows the distribution of flow fields at 700 hPa in Dehong Prefecture at 08:00 on May 11 to 16 in 2022. On May 11, it was controlled by the westerly airflow from the periphery of the Bay of Bengal, and even in Myanmar, it could be regarded as a weak "ridge-shaped" airflow, with a wind speed ranging from 8 to 10 m/s. On May 12, it was controlled by the westward airflow, and there was a weak cyclonic circulation in the northwest of Yingjiang County, with a wind speed of 8 – 10 m/s. On May 13, northwest airflow strengthened, and it was mainly controlled by the northwest airflow in front of the ridge, with a wind speed ranging from 6 to 10 m/s. The wind speed in Yingjiang County was relatively weak, only 6 m/s. On May 14, a shallow trough was generated in Bangladesh, and it was mainly controlled by the shallow westward airflow. Wind speed increased, ranging from 10 to 12 m/s. On May 15, the trough gradually weakened to westward airflow, and wind speed also decreased to 10 m/s. On May 16, another shallow trough was generated in Bangladesh again, but wind speed gradually reduced to 1 – 6 m/s, and the dynamic conditions weakened.

The distribution of flow fields at 850 hPa in Dehong Prefecture at 08:00 on May 11 to 16 in 2022 can be seen in Fig. 13. From May 11 to 16, wind speed reached 6 m/s along the western edge of Dehong. The coverage area of high wind speed increased from May 11 to 15, and gradually declined on May 16. The wind speed of the southwest jet reached 6 – 8 m/s from May 11 to 16, and it was higher on May 14 and 15. The maximum wind speed reached 12 – 14 m/s, and the outlet area was aimed at the west and north of Yingjiang. The actual situation show that the maximum rainfall on May 15 was 125.3 mm in Sudian in the northwest of Yingjiang.

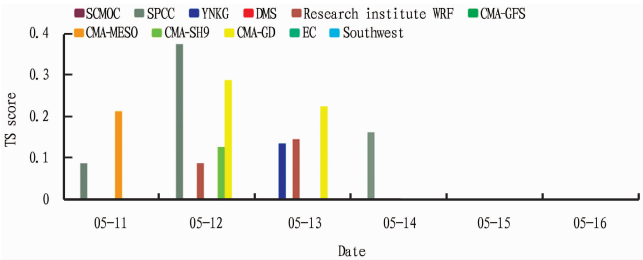


Fig. 9 Changes in the TS score of rainstorms in Dehong Prefecture from May 11 to 16 in 2022

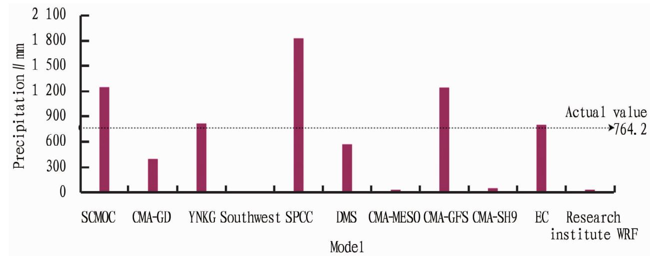
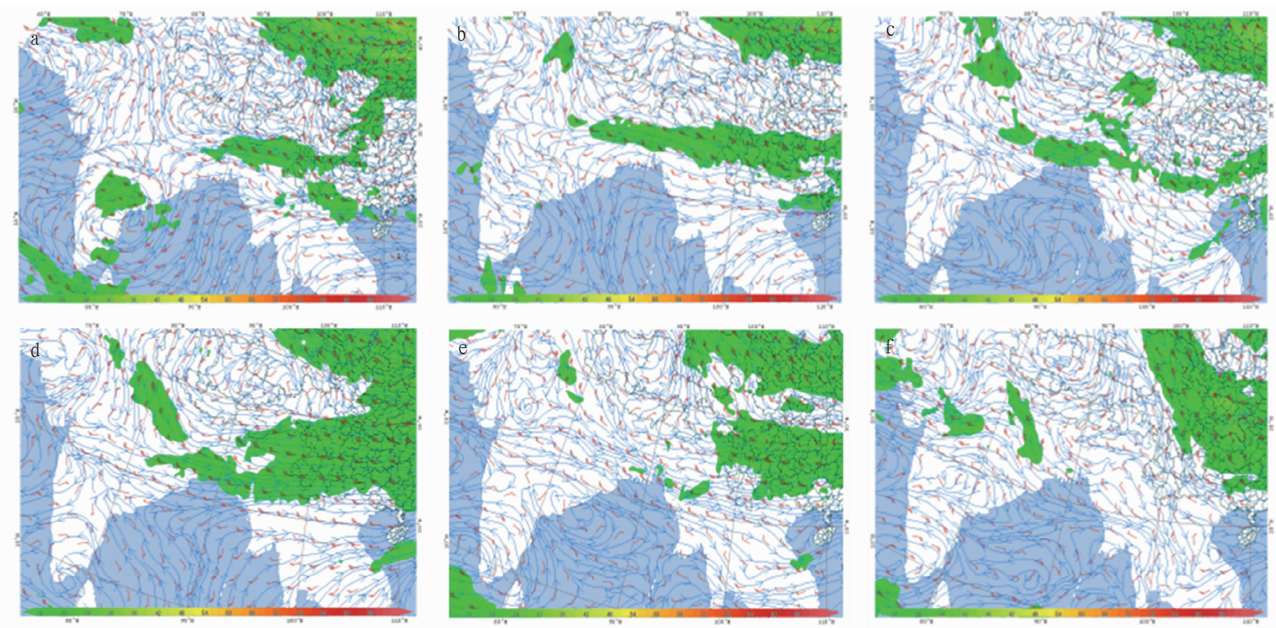
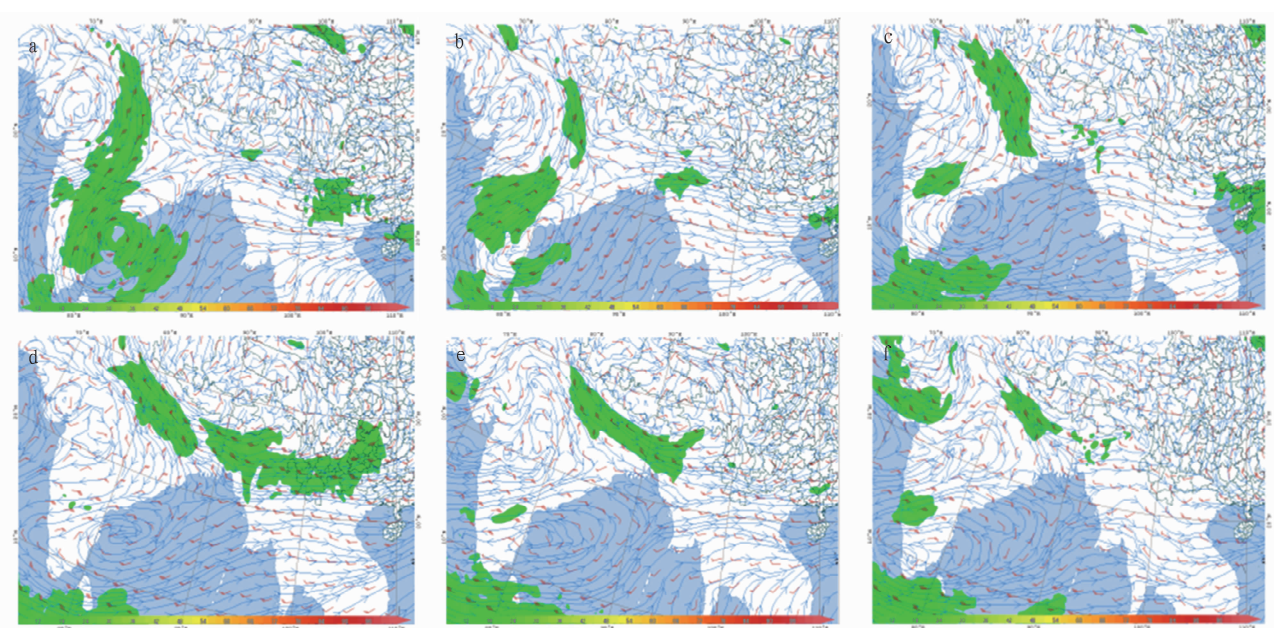


Fig. 10 Model forecast error of cumulative precipitation in Dehong Prefecture from May 11 to 16 in 2022



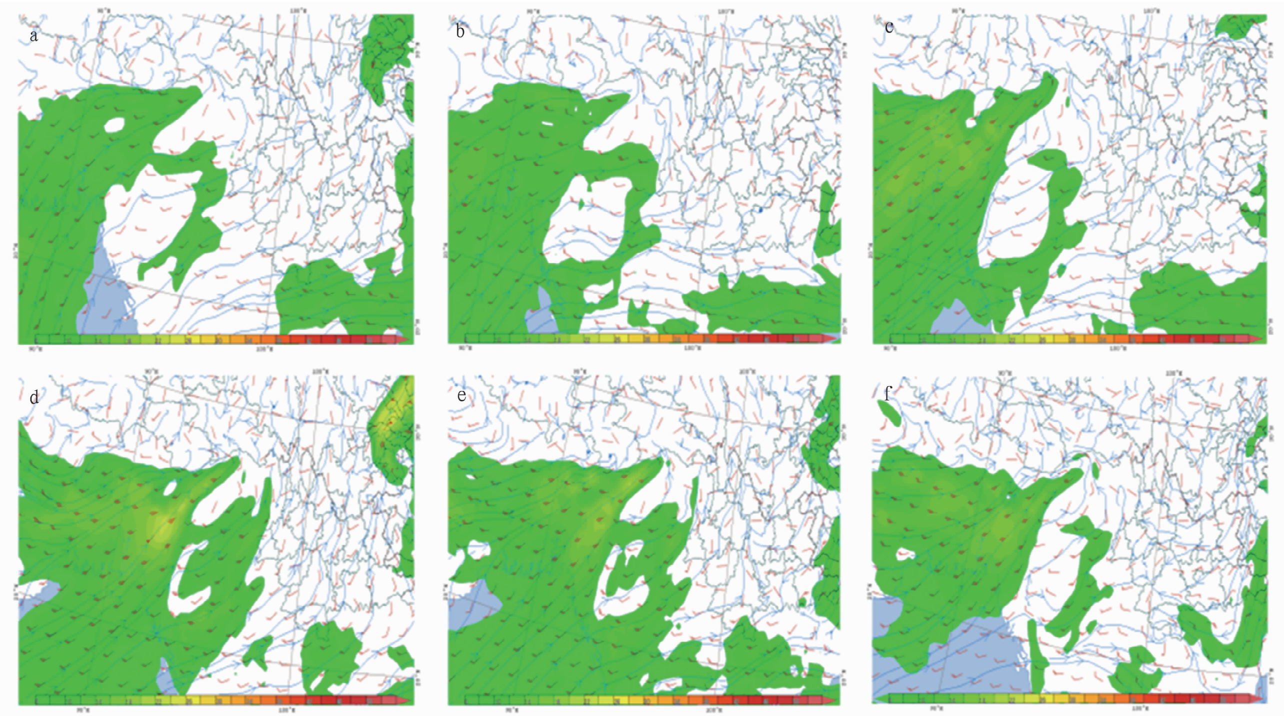
Note: Fig. a – Fig. f respectively represent the maps at 08:00 from May 11 to 16.

Fig. 11 Distribution of flow fields at 500 hPa in Dehong Prefecture at 08:00 from May 11 to 16 in 2022



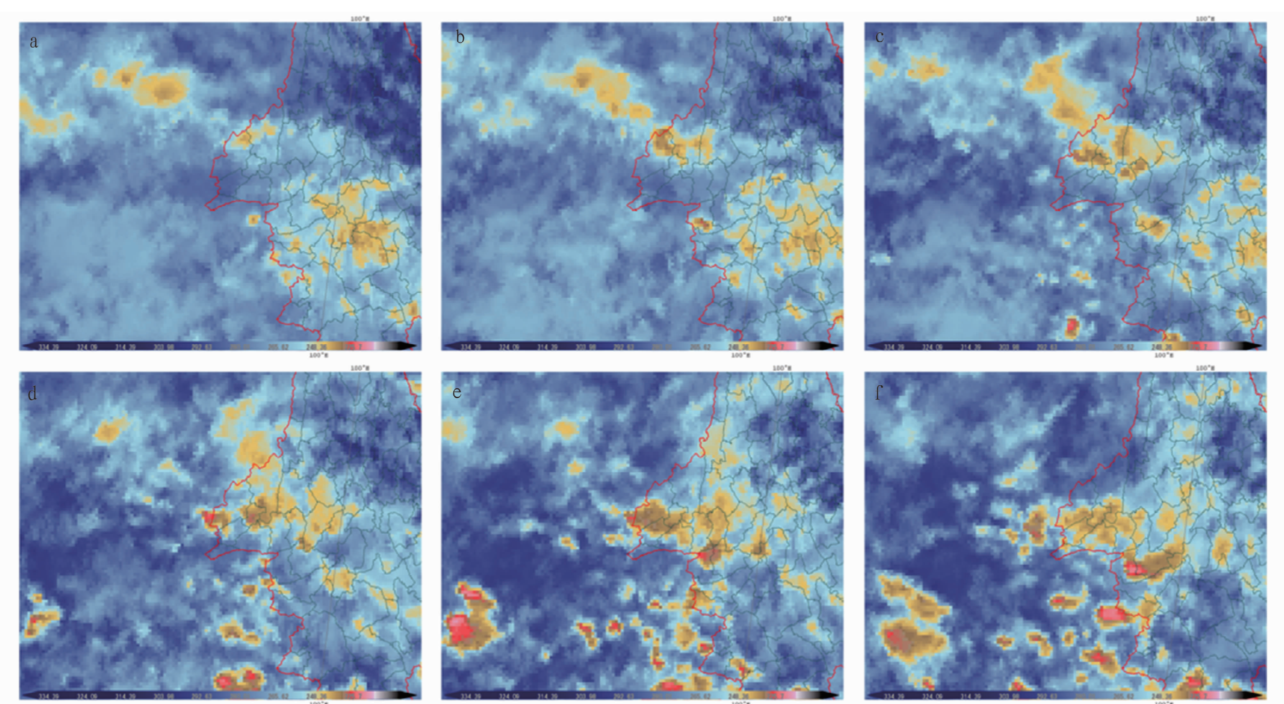
Note: Fig. a – Fig. f respectively represent the maps at 08:00 from May 11 to 16.

Fig. 12 Distribution of flow fields at 750 hPa in Dehong Prefecture at 08:00 from May 11 to 16 in 2022



Note: Fig. a – Fig. f respectively represent the maps at 08:00 from May 11 to 16.

Fig. 13 Distribution of flow fields at 850 hPa in Dehong Prefecture at 08:00 from May 11 to 16 in 2022



Note: a. 12:00; b. 13:00; c. 14:00; d. 15:00; e. 16:00; f. 17:00.

Fig. 14 Evolution of FY-4 Satellite Infrared Cloud Images in Dehong Prefecture from 12:00 to 17:00 on May 11 in 2022

3.2 Fine development and evolution of small-scale systems (including analysis of comprehensive observation data of satellites and radars)

3.2.1 Analysis of infrared satellite cloud images. The FY-4 infrared cloud images from 12:00 to 17:00 during the heavy rainfall process on May 11 were analyzed. As shown in Fig. 14, the cloud clusters with lower cloud top brightness temperature were mainly distributed in the north of Yingjiang at 12:00. From 12:00 to 13:00, hourly rainfall intensity was the largest in Nangbang in Yingjiang, up to 29.0 mm. At 14:00, part of the cloud clusters in the west of Yingjiang moved out of Dehong and reached Tengchong, while another part moved to Lianghe. With the strengthening of southwest jet, the stronger cloud clusters mainly covered the west of Yingjiang and Lianghe at 15:00. At this time, the cloud top brightness temperature was approximately 220 – 240 K. According to the actual rainfall situation, short-term heavy rainfall occurred in Nongzhang in Yingjiang from 13:00 to 14:00 and from 14:00 to 15:00, and precipitation reached 30.0 and 34.0 mm, respectively. Light to moderate rainfall appeared in other areas. From 15:00 to 17:00, convective cloud clusters continuously entered Dehong from the west, and there were still convective cloud clusters in the west of Yingjiang and the north of Longchuan. Therefore, the maximum hourly rainfall intensity occurred in Xie Li Village in Yingjiang from 15:00 to 16:00, up to 30.7 mm. From 16:00 to 17:00, short-term heavy rainfall occurred in Pingshan in Longchuan, and hourly rainfall intensity was up to 27.9 mm. After 17:00, strong convective cloud clusters gradually weakened as the distance increased. Light rain happened mostly in Dehong, and the precipitation process weakened significantly.

3.2.2 Analysis of radar data. The evolution of radial velocity of CINRAD/CD Doppler radar in Dehong from 02:00 to 14:00 on May 15 is shown in Fig. 15. It is found that the evolution of wind field during this rainfall process was very obvious, and could better reveal the system's evolution. Since 02:01, cloud systems of rainfall began to affect the north of Yingjiang. The radial velocity field shows that there was northwest wind intrusion in the north. As the cloud systems slowly moved, westerly and northeasterly winds strengthened at 03:03, and there was significant convergence in the west of Yingjiang. This indicates that cold air was gradually affecting the north of Dehong along the Hengduan Mountains. At 04:00, a tailwind area (9 – 14 m/s) appeared in the north of Yingjiang, and the corresponding positive velocity area did not have a large wind area. This reveals that there was already a strong convergence zone of wind speed in the north of Yingjiang. At this time, the short-term heavy precipitation at Sudian station had reached the maximum 27.4 mm. The tailwind area developed at an elevation of 2.4°, and there were 17 – 35 dBZ echoes on the intensity map, and the echo top height was 4 – 6 km. This indicates that it was mainly rainfall at this time. As the tailwind area gradually strengthened, the mesoscale convergence intensified, and the echoes continued to develop. At 06:00, a "儿" shaped convergence echo of southwest-northeast-western wind appeared in the north of Yingjiang in the radial velocity field. Wind direction convergence continued to strengthen. At 07:03, the "儿" shaped echo convergence still existed. After 08:00, the convergence gradually weakened, but there were still weak echoes in the northwest of Yingjiang. At this time, it had turned to light rain, and the process gradually came to an end.

3.3 Diagnostic analysis of key physical quantities

3.3.1 Analysis of unstable energy. This heavy rainfall was mainly continuous and stable precipitation brought by low-altitude jet. Only on the TlnP map at 08:00 on May 16, cape value reached 1 036.8, while cape values in other times were all less than 1 000; CIN was all 0 (the figure is omitted). There was some convective unstable energy in this process, but it was not strong. Hence, the precipitation was mainly convective, and severe convective weather was not prominent.

3.3.2 Analysis of moisture conditions. The evolution of specific humidity q and relative humidity r in Dehong Prefecture at 08:00 from May 11 to 16 is shown in Fig. 16 and Fig. 17. During this heavy rainfall process, water vapor conditions were relatively low on May 15, and specific humidity q ranged from 7 to 10 g/kg, while relative humidity r varied from 65% to 90%. During other periods, specific humidity did not change much, ranging from 8 to 11 g/kg; relative humidity r ranged from 76% to 99%, so there were adequate water vapor conditions.

3.4 Analysis of causes of forecast deviation for heavy precipitation The main reasons for the forecast deviation of heavy precipitation are as follows. This heavy rainfall process had an atypical weather situation, so the forecasting experience could not be fully utilized. In a weak situation field, there was no obvious precipitation system at 500 hPa and no obvious southward trough at 700 hPa. Only at 850 hPa, there was a southwest jet. Moderate to heavy rain with local rainstorms and heavy rainstorms occurred mostly in Dehong Prefecture.

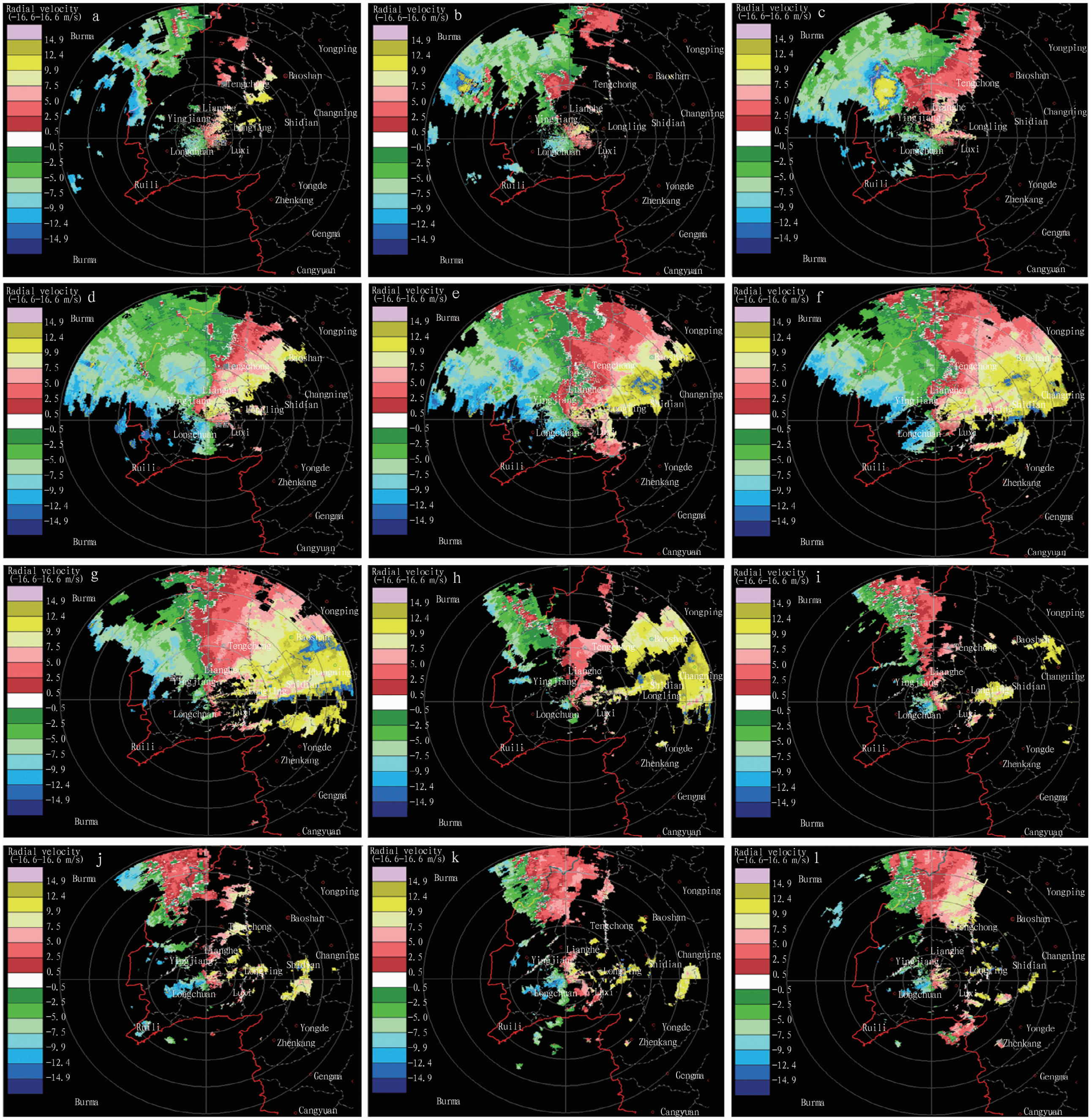
The altitude in the west and north of Yingxiang is relatively high, and there was a significant windward slope effect. The terrain has a significant influence on rainfall. Attention should be paid to the convergence of wind speed and wind direction at the lower levels. Generally, water vapor conditions in summer are good, and the movement and development of the system should be closely monitored.

The forecast accuracy of this process based on the models is insufficient. Among the 8 models on the Yunnan Intelligent Forecast Platform, the prediction level of rainfall was lower than the actual level during May 11 – 15, while it was higher than the actual level on May 16. On May 11, the surface prediction result of 6 models (CMA-MESO, CMA-GD, EC, YNKG, research institute WRF, and SPCC) was light to moderate rain with local heavy rain. On May 12, that of 3 models (CMA-MESO, EC, and YNKG) was light to moderate rain with local heavy rain. On May 13, that of 6 models (CMA-GD, research institute WRF, CMA-GFS, EC, YNKG, and CMA-SH9) was light to moderate rain with local heavy rain. On May 14, that of 5 models (CMA-GD, EC, CMA-GFS, SPCC, and CMA-SH9) was light to moderate rain with local heavy rain. On May 16, that of CMA-SH9 and research institute WRF was moderate to heavy rain with local rainstorms.

4 Improvement ideas and countermeasures for forecast services

4.1 Analysis thoughts and focus of heavy rainfall prediction

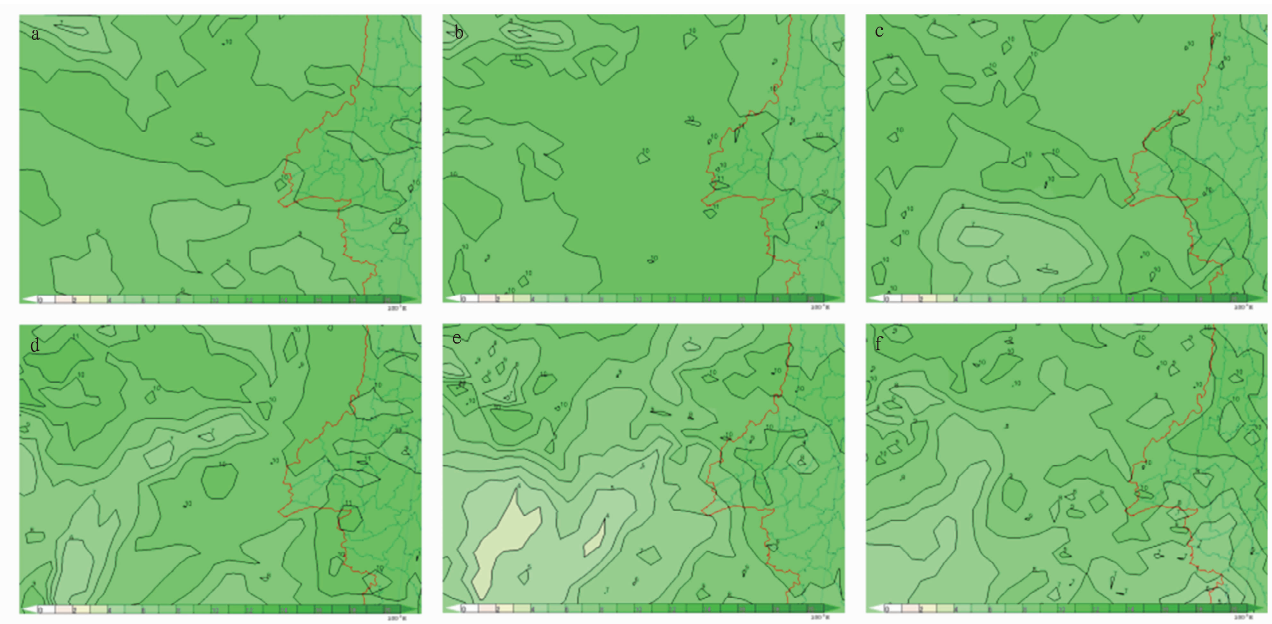
Based on the difficulties in forecasting this heavy rainfall process,



Note: a. 02:01; b. 03:00; c. 04:00; d. 05:03; e. 06:00; f. 07:03; g. 08:00; h. 09:48; i. 11:02; j. 12:05; k. 13:02; l. 14:04.

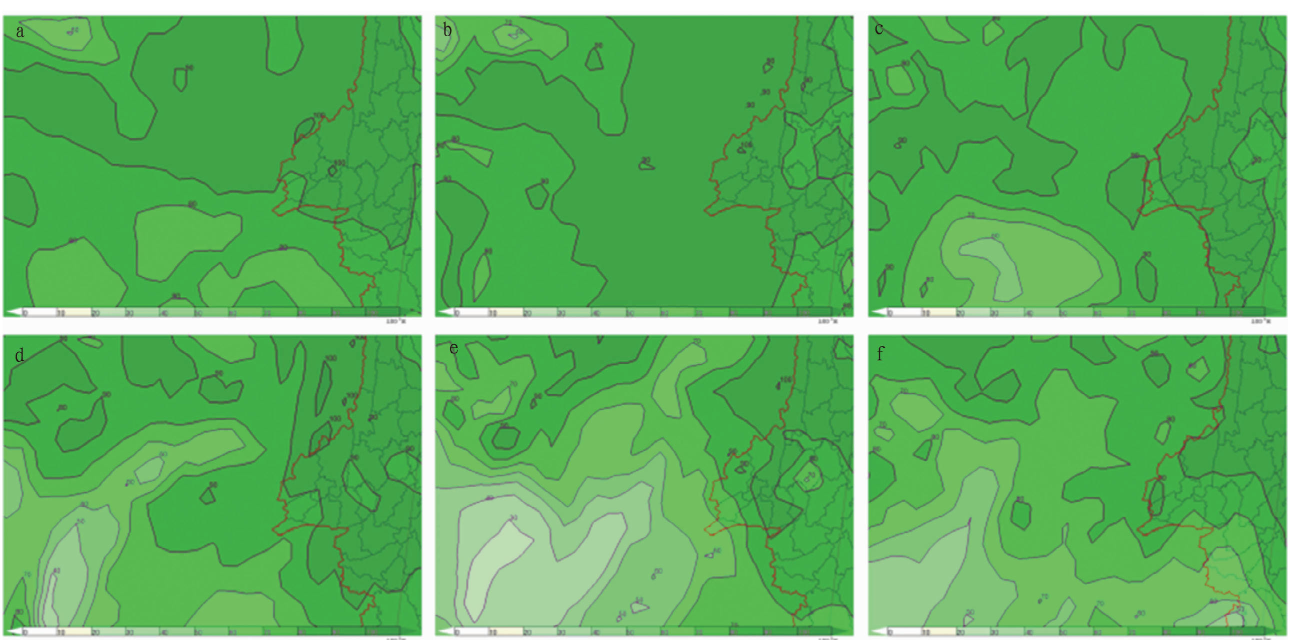
Fig. 15 Evolution of radial velocity of Doppler radar in Dehong Prefecture from 02:00 to 14:00 on May 15 in 2022

there was no typical precipitation weather pattern at the higher level, and the numerical models failed to provide good forecast results for such weather phenomena. Additionally, the western and northern parts of Yingjiang have higher altitudes, which facilitates atmospheric convergence and upward movement. In case of abundant water vapor, it is very likely to form rainstorms and heavy rainstorms. Therefore, the analysis thoughts and focus of such heavy rainfall prediction are as follows. (1) Starting from May, due to the influence of southwest airflow, the water vapor conditions in Dehong Prefecture were good. The relative humidity at 700 hPa was above 70%. That is, even if there was no obvious precipitation system at 500 and 700 hPa, the possibility of rainstorms should be considered when wind speed was greater than 6 m/s at 850 hPa, and the exit was aimed at Dehong. The large wind speed zone at 850 hPa has important indicative significance for heavy precipitation. (2) During the flood season with good water vapor conditions, for the profile graph of a certain point in the "model profile" of analysis tools in micaps, if there is a clear dynamic feature, positive vorticity development at 850 – 700 hPa, and the characteristics of convergence at the lower level and divergence at the upper level, the possibility of heavy precipitation should be considered. (3) Rainstorm echoes were associated with "儿" shaped convergence echoes. When there was obvious wind speed or wind direction convergence on the radar map of radial velocity, and convection would continue to strengthen, heavy precipitation and short-term heavy precipitation would happen. (4) Paying attention to the parameters such as the radial velocity field, echo reflectivity, and any vertical profile of the new generation of Doppler radar has important roles in the development of the prediction system.



Note: a. May 11; b. May 12; c. May 13; d. May 14; e. May 15; f. May 16.

Fig. 16 Evolution of specific humidity q in Dehong Prefecture at 08:00 from May 11 to 16 in 2022



Note: a. May 11; b. May 12; c. May 13; d. May 14; e. May 15; f. May 16.

Fig. 17 Evolution of relative humidity r in Dehong Prefecture at 08:00 from May 11 to 16 in 2022

4.2 Improvement ideas and technical solutions for the deviation of heavy rainfall forecast on June 7, Dehong Meteorological Bureau organized a review and summary of the first large, intense and long-lasting heavy rainfall process in Dehong Prefecture from May 11 to 16. The improvement ideas and technical solutions for the deviation of heavy rainfall forecast are as follows. (1) The southwest jet axis at 850 hPa is of great reference significance. Even if there was no obvious southward branch trough at the upper level, heavy precipitation would still form. The wind speed at the exit of strong wind speed zone of the southwest jet decreased sharply, forming wind speed convergence. The warm and humid air from the southwest, carrying relatively sufficient water vapor and energy, is prone to form heavy precipitation under the action of dynamic uplift. Forecasters should pay attention to the forecast of the exit of the southwest airflow with a wind speed of > 6 m/s at 850 hPa, and the precipitation level can be appropriately increased. (2) The reference significance of models used in such heavy rainfall processes is very limited. Through analysis, it is found that the forecast of heavy rainfall was mainly based on the CMA-GFS model, while the forecast of rainstorms mainly referred to regional models CMA-GD and CMA-SH9; the research institute WRF model was also worth reference. For such processes, it is necessary to continue to timely test the forecast results of various models and obtain more applicable local forecast methods. (3) Through the analysis of this process, it is found that for the forecast of the exit of the southwest airflow with a wind speed of > 6 m/s at 850 hPa, and quantitative research on the increase in precipitation level and the area affected by the formation of wind speed convergence at the exit of high wind speed longer time scales of data, more cases, and more scientific and localized methods are needed, and the underlying mechanism still requires further in-depth research.

4.3 Service improvement ideas and suggestions During this heavy rainfall process, the decision-making meteorological services, and the release of warning information and risk warnings were timely, and service effects were good. All departments promptly took preventive measures to minimize casualties to the greatest extent, and meteorological departments effectively played its role as the "first line of defense for disaster prevention and mitigation". The important weather forecasts and warnings released to the public were widely known and received high attention. The ideas for improving future meteorological services are as follows.

(1) The release of decision-making meteorological services should focus on the analysis of current weather conditions[11]. Timely warnings should be issued, and the "1262" service should be provided to relevant emergency management departments. During a heavy rainfall process, short-term heavy rainfall may cause geological disasters such as landslides and mudslides, as well as mountain floods, and these disasters are more likely to occur; cumulative heavy rainfall may lead to landslides, flash floods, rising water levels in small and medium-sized rivers, and other types of floods and water disasters. Therefore, when there is a possibility of heavy rainfall, forecasters should issue a corresponding warning of rainstorms and provide "1262" progressive meteorological services in advance based on the actual conditions. When issuing the warnings, forecasters should also track the process and promptly analyze the differences between the actual conditions and forecast results, and use short-term means to correct the forecast and update the warnings, and "1262" progressive service products in a timely manner. For example, as the actual precipitation is up to 25 mm, it is predicted that precipitation will be more than 25 mm within the next 12 h, a blue rainstorm warning should be issued promptly, rather than issuing it until the actual rainfall reach 40 mm. Then the emergency management departments should have enough time to prepare rescue forces and transfer threatened people. Since the flood season in 2022, the "1262" service model implemented, with the intelligent forecasting platform of Yunnan Province as the technical support, is actually a supplement to the warning and a way to urge forecasters to regularly check the rainfall situation and timely issue products, so it is a very good means of disaster prevention and mitigation.

(2) It is suggested to establish a complete decision-making meteorological service system and then form an authoritative, standardized and regulated decision-making meteorological service system[12]. In the context of modern disaster prevention and mitigation, there are many national, provincial, municipal and county-level meteorological service products; there are decision-making meteorological service products including medium- and long-term forecast, special reports on important meteorological information, important weather forecast, 24-hour forecast, warnings, and "1262" service products. The staff of other departments may not have a good grasp of the key points of these meteorological service products, or they may not know how to use these products. Therefore, meteorological departments need to do more popular science explanations to the outside world, and promote these meteorological service products from multiple perspectives and at multiple levels. Secondly, it is hoped that meteorological departments should strengthen technology introduction and establish a standardized and regulated decision-making meteorological service platform or system for all levels of meteorological departments across the province and even the whole country. For instance, warnings are released by the "12379" number to relevant personnel of each decision-making department throughout the country. Warnings are all classified by colors from high to low, namely "red, orange, yellow and blue", which is more universal.

5 Conclusions and discussion

(1) This heavy rainfall process was a warm-sector rainstorm caused by the strong southwest jet at 850 hPa under the background of a weak weather scale. Under the circulation background, there was dry and cold northwest airflow and no high-altitude trough at 500 hPa, and no obvious south branch trough existed at 700 hPa. At 850 hPa, there was a southwest jet with a wind speed of $\geq$ 6 m/s, and the wind speed at the jet stream core reached 10 – 16 m/s. There was vigorous southwest warm and humid air flow in the middle and lower levels and no shear lines or obvious shear lines. Rainstorms usually appeared at the exit of the jet stream axis where there was wind speed convergence and abundant water vapor.

(2) The characteristics of the rainstorm process under the influence of the strong southwest jet were wide coverage and high intensity, and it was prone to cause geological disasters, mountain

floods and other secondary disasters. This process lasted for 6 d, totaling 144 h. The top three stations with the largest cumulative rainfall during the process were Sudian (370.2 mm), Mengdian River (366.4 mm), and Kachang (364.4 m) in Yingjiang County. In Dehong, there were heavy rainstorms at 7 stations, rainstorms at 118 stations, and heavy rain at 237 stations. Such process mainly occurs in spring. Under the combined influence of the mesoscale boundary layer and topographic effects, warm and humid air is lifted, and unstable energy is released to generate rainstorms. Moreover, such weather process can happen at any time during the day and last for multiple periods, and the frequency of precipitation at night increases[3].

(3) The application of mesoscale data of satellites and radars has provided a basis for identifying and tracking such mesoscale weather systems, and the forecasting and warning of rainstorm weather. Yingjiang County has a relatively high altitude, and the uplifting effect of the terrain is an important factor for such weather processes, providing certain dynamic uplifting effects for the cloud clusters of rainstorms. The lower-level water vapor convergence zone corresponds with the wind field convergence zone affected by the terrain, and the intensity of water vapor convergence is much greater than that of water vapor convergence brought by large-scale systems, which is the main reason for the widespread occurrence of rainstorms and the occurrence of local heavy rainstorms[10].

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