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Analysis of the Heavy Rainfall Process in Mangshi City on August 8, 2023

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Abstract On August 7, 2023, Mangshi City, Dehong Prefecture experienced a local heavy rainstorm, and the geological disaster caused by the heavy rainfall caused casualties and property losses. Based on the real-time observation data of automatic stations, Doppler weather radar detection and meteorological risk warning products, the disaster situation, social impact, forecast and early warning service, causes of heavy precipitation and forecast and early warning inspection were summarized and analyzed. The results show that the heavy rainfall was prominent locally, lasted for a long time and accumulated a large amount of rainfall. There were biases in model products, and it was difficult for forecasters to make subjective corrections in complex terrain. The analysis ideas and focus points of heavy rainfall forecast, the improvement ideas and technical schemes of forecast deviation, and the improvement ideas and suggestions of services were summarized. It provides a reference for the forecast and early warning of severe weather in the future.

Key words Heavy rainfall; Low-pressure inverted trough; Geological disaster; Forecast deviation

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In Dehong Prefecture, Yunnan Province, geological disasters are frequent, and are mainly distributed in Mangshi, Lianghe and Yingjiang. Dehong Prefecture is located to the south of the Hengduan Mountains and the west of the Gaoligong Mountains. The terrain is high and steep in the northeast but low and wide in the southwest; steep slopes are widely distributed, and gully and valley are cut strongly. Due to its location in the eastern margin of the collision zone between the Eurasian plate and the Indian Ocean plate, earthquakes occur frequently, and tectonic movements are strong. Active fault zones are dense, and unstable rock and soil are extensive. Fragile geological conditions provide material basis for the formation and development of geological disasters, which are very likely to cause geological disasters such as flash floods, debris flows and landslides[1 –2]. The main inducement factor of geological disasters such as mountain torrents, mud-rock flows and landslides are heavy precipitation. Heavy precipitation events in Yunnan are characterized by high precipitation intensity, wide range, large amounts of rainfall and long duration, with significant seasonal, sudden, concurrent and regional characteristics[3 –10]. In addition, Dehong Prefecture is located in the windward slope area, which is uplifted from the northeast end of the low-elevation trumpet terrain area in central and western Myanmar to the west of Yunnan, and the topographic conditions are extremely conducive to the development and strengthening of precipitation cloud system. With the increasing influence of climate change on extreme weather and climate events in Yunnan, the intensity and frequency of heavy precipitation have increased, which has increased the risk of mountain flood geological disasters, and especially the increase of heavy precipitation events in the main flood season has resulted in an increase in the frequency of geological disasters such as mountain torrents, mud-rock flows and landslides. In 2023, Dehong Prefecture suffered frequent heavy rainfall weather processes and strong convection weather, and prominent thunderstorms and gale disasters, and heavy rainfall led to floods, flash floods, landslides, debris flows and other disasters in many places throughout the prefecture, which adversely affected people's production and life. In the year, 26 times of heavy rain and flood disasters and one geological disaster occurred in all counties of Dehong Prefecture, resulting in a total of 5 deaths and a total economic loss of 337.768 7 million yuan. It can be seen that the frequent occurrence of geological disasters seriously has threatened the life and property safety of people in mountainous areas, so disaster prevention and reduction are urgent[11 –15].

Affected by the southwest air flow and the low overrunning trough, from 08:00 on August 7 to 08:00 on August 8, 2023, Dehong Prefecture experienced moderate-to-heavy or local rainstorm weather, among which Mangshi experienced local heavy rainstorm. Landslides occurred in Mangshi Town, Zhongshan Township, Fengping Town, Santaishan Township, Wuchalu Township, Xishan Township, Zafang Town, Manghai Town, Mengjia Town,

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resulting in 3 deaths, one injury, and direct economic losses of 12.511 2 million yuan. In this paper, based on the real-time observation data of automatic stations, Doppler weather radar detection data, and meteorological risk warning products and other data, the causes and forecast services of a local heavy rainfall process in Mangshi, Dehong Prefecture on August 7, 2023 were studied, and the experience of forecast services were summarized. Besides, existing problems and shortcomings were discussed to provide reference for the meteorological service guarantee work of disastrous weather in the future.

1 Actual situation of the geological disaster

From 08:00 on August 7 to 08:00 on August 8, there was a heavy rainstorm in Mangshi, Dehong Prefecture, and due to the combined effect of sustained heavy rainfall in the earlier period, various degrees of disaster appeared in several townships of Mangshi, Dehong Prefecture, resulting in casualties and serious economic losses. The disaster affected 2 947 people, among which 3 people were killed, and 1 people injured, while 652 people were urgently relocated; the affected area of crops was 122.36 hm^2, and 2 farming houses and 2 rooms were severely damaged; infrastructure was damaged to varying degrees. The direct economic loss reached 12.511 2 million yuan.

The disaster is mainly divided into two stages. In the first stage, a landslide and collapse occurred on the 8^{th}. At 06:40, a landslide appeared in Songyuanjiao, Mengmu Village, Songshuzhai Village Committee, Mangshi Town, so that one person injured, and two people died. At 07:44, the road in Huixian Village Mangshi Town collapsed, so that one house was destroyed, and one people died. In the second stage, sustained moderate-to-heavy rain in the later period led to floods and other meteorological derived disasters in other places in Mangshi. The results of the geological disaster in the first stage were caused by both human and natural factors. Seen from the daily precipitation ten days before the concurrence of the disaster in regional meteorological stations Mangshi station and Shangdong station that were the closest to the disaster point (Fig. 1), under the influence of the shear line and warm and moist air, the rainfall in the early period lasted for a long time, and the accumulated rainfall during the process was large. Stable precipitation was dominant. On the day before the concurrence of the disaster, a heavy rainstorm of 123.1 mm occurred in Shangdong station. The precipitation was concentrated between 22:00 on the 7^{th} and 03:00 on the 8^{th}, and the cumulative rainfall reached 103.1 mm in 12 h (from 20:00 on the 7^{th} to 08:00 on the 8^{th}). The rainfall intensity was the highest at 01:00 on the 8^{th}, up to 24.6 mm. The precipitation in Mangshi station was 73.9 mm the day before the disaster, and the cumulative rainfall within 12 h (from 20:00 on the 7^{th} to 08:00 on the 8^{th}) was 58.9 mm, without short-term heavy precipitation. The heavy rainfall process was small in scope and prominent in locality, and was mainly concentrated in the eastern area of Mangshi. In terms of human factors, the disaster body was located in the construction lot of Ruimeng Expressway (Fig. 1c and Fig. 1d). Because the construction unit did not strictly implement the contents of the geological disaster risk assessment report, the site of the temporary workshop was improperly constructed. After the Mangshi Town People's Government issued a notice of prevention of natural disasters to the project department of Huixian Section of Ruimeng Expressway and the station of Ruimeng Tunnel on July 14, the construction unit still failed to prevent natural disasters as required in the notice. Due to the combination of the heavy rainfall on the day before the disaster and the accumulated precipitation in the previous period, the water of the rock and soil was saturated for many days, and the anti-sliding force of slopes decreased[16]. In addition, the construction disturbance reduced the stability of the rock and soil, and the surface soil was loosened, which eventually led to the instability of the rock and soil and formed landslide disaster.

2 Analysis of causes of heavy precipitation and forecasting difficulties

2.1 Development and evolution of major weather systems The disaster occurred in the main flood season, and multiple trough ridges in the middle and high latitudes over the altitude field at 500 hPa moved eastward. Over the western Pacific Ocean, No. 6 typhoon "Khanun" in 2023 continued to move northward. Affected by its circulation, a low inverted trough appeared in the Ailao Mountains at 08:00 on August 7 (Fig. 2a), extending from the northwest to the southeast, and it was northerly. The inverted trough gradually moved westward with the low-pressure system to affect Dehong, transiting Mangshi on the night of the 7^{th} (Fig. 2b), and guiding the northerly wind to the south. Shear lines are one of the major weather systems that cause rainstorm in Yunnan[17]. Compared with other weather systems, the shear line system occurs frequently, and its activity rules are chaotic. It often cooperates with other weather systems to cause large-scale heavy precipitation, so it is more difficult to forecast it. On August 7, the shear line at 700 hPa (Fig. 2c) remained steadily in the Ailao Mountains. At 20:00 on the 7^{th}, the shear line moved slightly westward, and Dehong Prefecture was on its southwest side. Combined with the convergence and uplift of the low-level jet (southwest airflow), it provided strong dynamic uplift conditions for heavy precipitation. At 850 hPa, during the day of August 7, the central intensity of the southwest airflow in the west of Dehong Prefecture was 10 – 12 m/s, and increased significantly after 17:00, up to 16 – 18 m/s at 20:00. It maintained until 05:00 on August 8, and weakened at 08:00, providing sufficient water vapor transport conditions for the generation and maintenance of heavy precipitation.

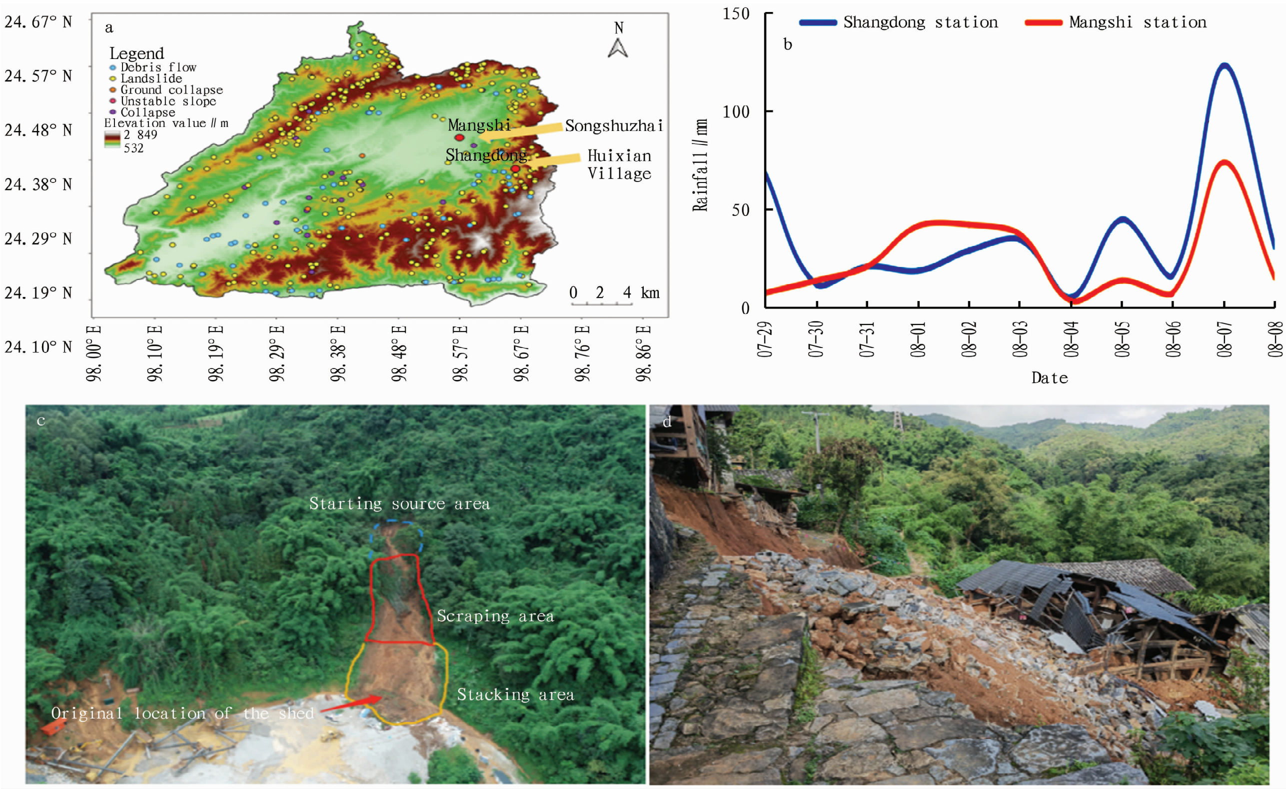


Fig. 1 Distribution of geological hazards in Mangshi (a), distribution of daily rainfall in meteorological stations near the disaster site (b), and disaster site maps (c, d)

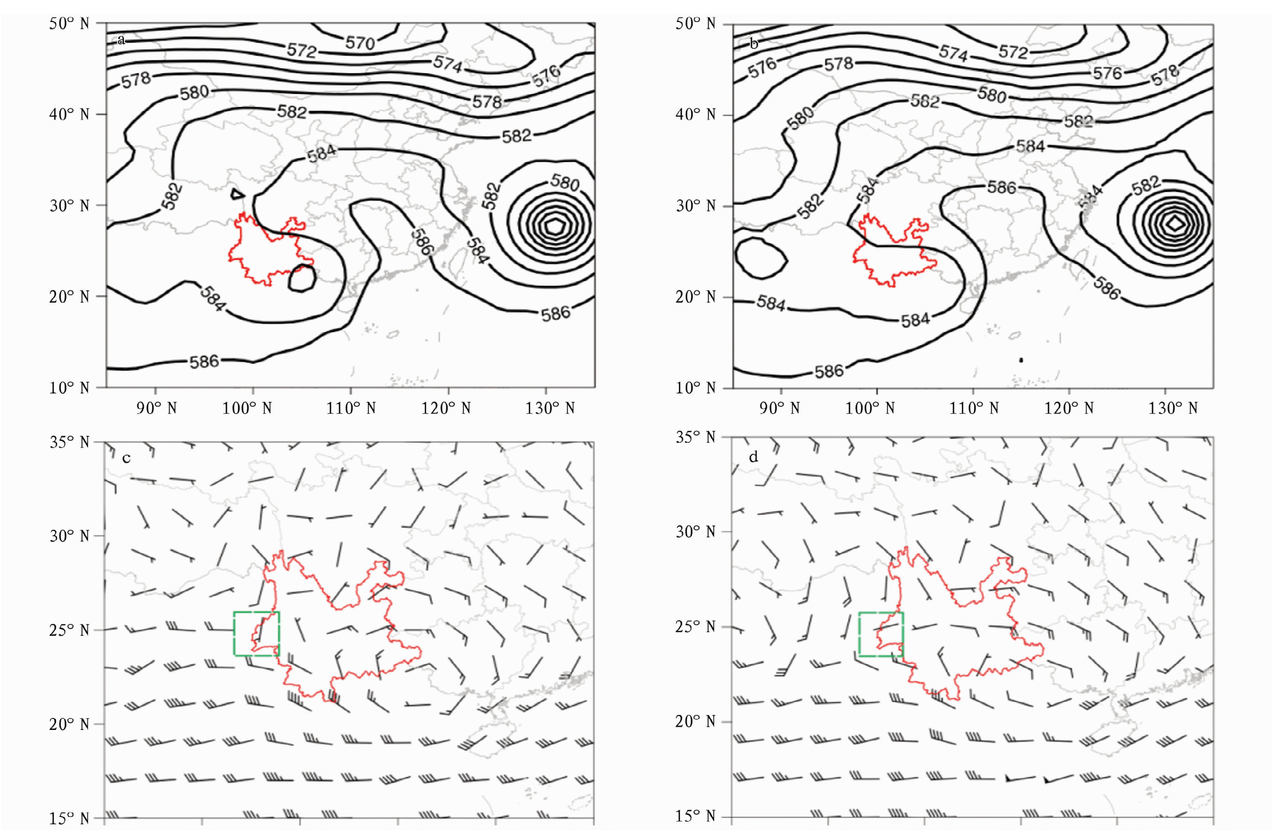
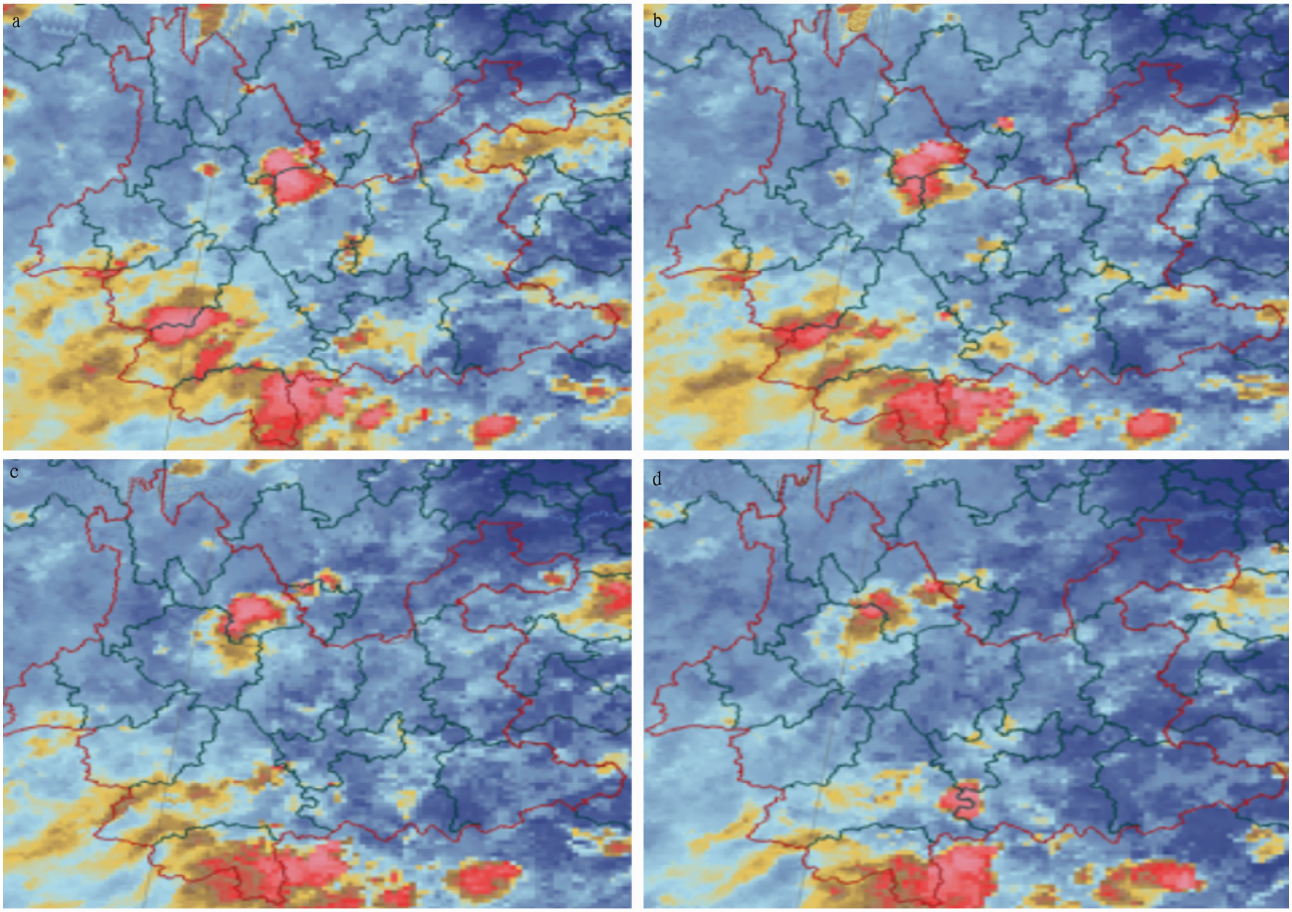


Fig. 2 High-altitude situation maps at 500 hPa at 08:00 (a, c) and 20:00 (b, d) on August 7 (a, b, unit: dagpm) and wind fields at 700 hPa (c, d, vector represents wind field; the dashed line area is the study area)

2.2 Fine development and evolution of small- and medium-scale systems Seen from the infrared cloud images, the mesoscale convective system developed in the central Yunnan in the evening, and gradually moved to the southwest under the guidance of the upper northeast airflow. After 20:00 on the 7^{th}, the convective cloud group gradually disintegrated, and the residual cloud system affected Mangshi. From the infrared cloud images during 00:00 – 03:10 on the 8^{th} (Fig. 3), it is seen that there was a precipitation cloud system in the central and southern part of Dehong, but the development of the cloud system was not very vigorous. The cloud system was dominated by low immostrus clouds, and the cloud system dissipated gradually. By 03:10, only a small cloud system remained over Mangshi. Therefore, the local heavy rainfall in Mangshi was generated by the maintenance of small- and medium-scale convective cloud systems. On the ground maps (not shown), there was a ground convergence line in the east of Dehong Prefecture from 20:00 to 23:00 on the 7^{th}, which provided a good triggering condition for the occurrence of heavy precipitation in Mangshi. In the time series diagram of instantaneous wind, the wind in Mangshi changed from the north to the east at 21:00, and converged with the upstream southwest wind, which provided the dynamic conditions for the generation of heavy precipitation.

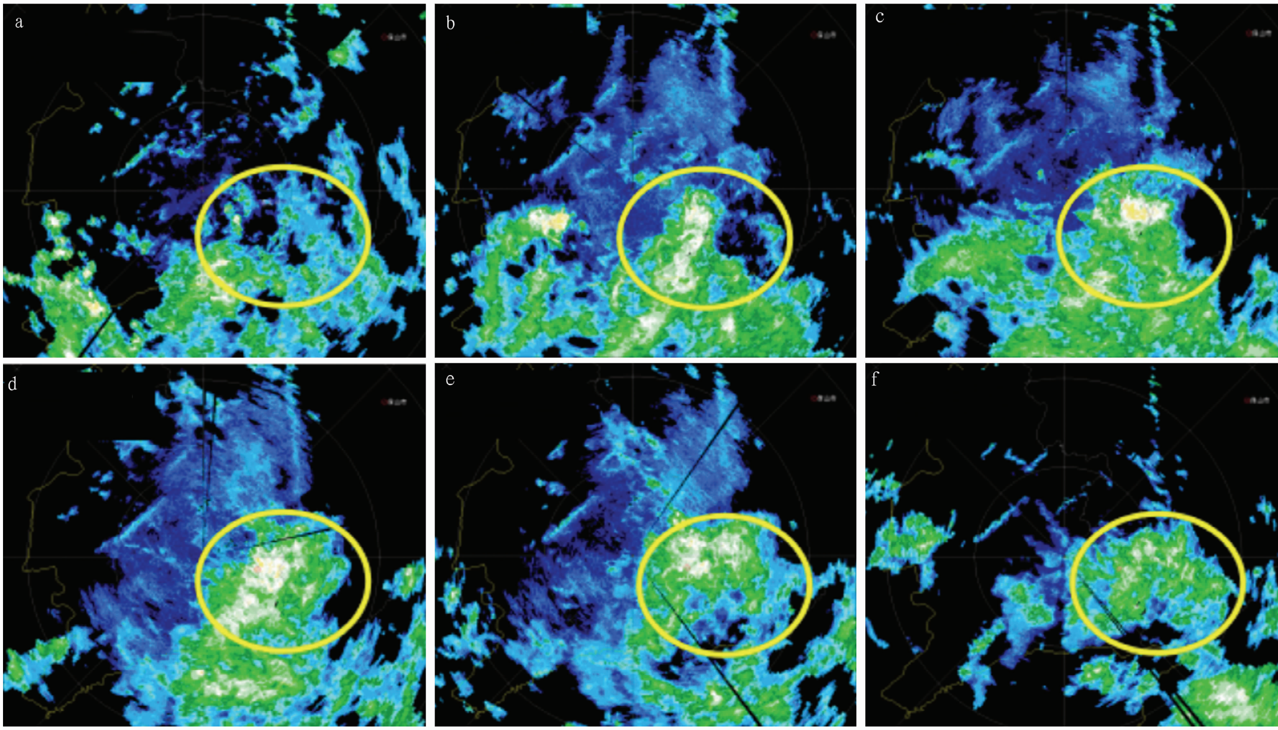


Note: a. 00:00; b. 00:50; c. 01:50; d. 03:10.

Fig. 3 Infrared cloud images from 00:00 to 03:10 on August 8

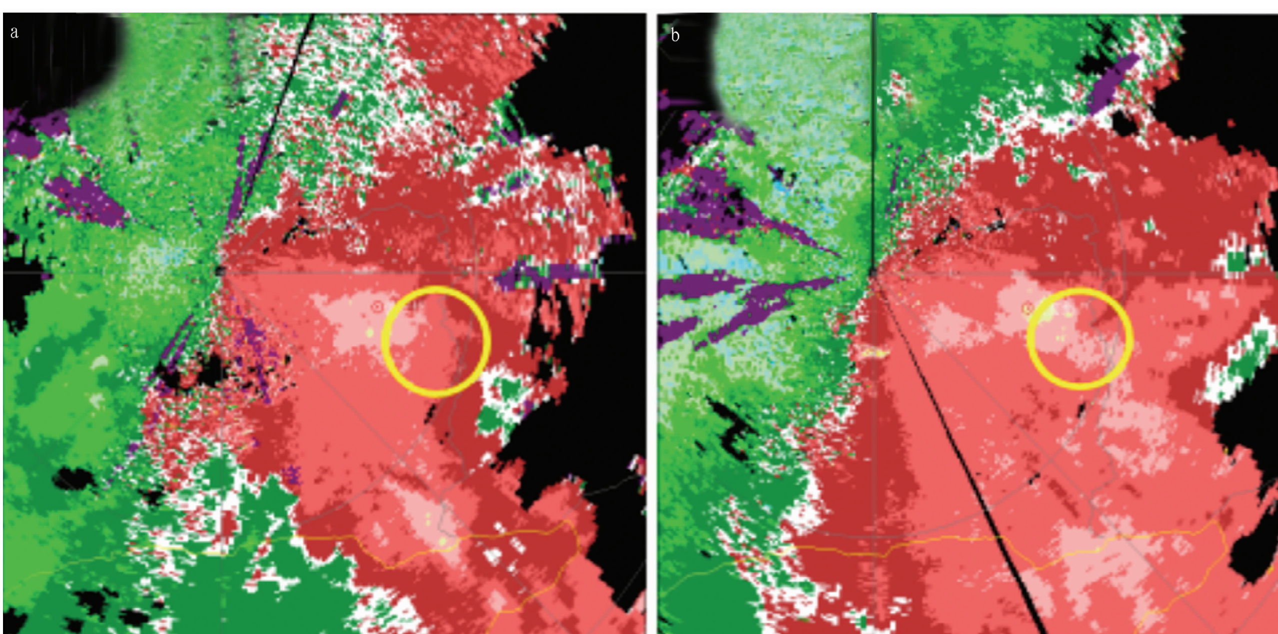
It can be confirmed from the basic reflectivity maps of Doppler weather radar that the echoes in Manshi gradually developed and strengthened from the southwest side after 20:00 on the 7^{th}, with a maximum intensity of about 40 dBZ. The echoes were dominated by dense stratiform cloud precipitation echoes and stratified mixed cloud precipitation echoes. The distribution of rainfall intensity was more uniform, and the features of convective rainstorm were not obvious. The precipitation echoes remained stable for nearly 6 h, so that stable precipitation lasted for a long time in Mangshi. As can be seen from the basic reflectivity map at 04:00 on the 8^{th} (Fig. 4e), the echoes in the south had begun to dissipate and become loose, indicating that the echoes had begun to weaken, and cumulus echoes weakened into a large area of stratus cloud echoes. By 07:00 on the 8^{th} (Fig. 4f), the strength of the echo body greatly weakened, and the range reduced; the echoes became scattered, and the precipitation was about to end.

As shown in the radar radial velocity maps (Fig. 5), from 23:00 on the 7^{th} to 02:00 on the 8^{th}, there was a convergence area of continuous wind direction and speed over Shangdong station, and there was a headwind area in the east of Mangshi. As a result, the echoes were stable and less moved, and strengthened in the convergence area. The eastern part of Mangshi was blocked by mountains and located on the windward slope. Affected by terrain convergence and enhanced dynamic uplift, it was conducive to the continuity and increase of precipitation. Until 03:00 on the 8^{th}, the large wind speed area behind it gradually moved eastward out of Mangshi, and the precipitation began to weaken.



Note: a. 20:00 on the 7^{th}; b. 22:00 on the 7^{th}; c. 00:00 on the 8^{th}; d. 02:00 on the 8^{th}; e. 04:00 on the 8^{th}; f. 07:00 on the 8^{th}.

Fig. 4 Basic reflectivity maps of Doppler weather radar from 20:00 on the 7^{th} to 07:00 on the 8^{th}



Note: a. 23:00 on the 7^{th}; b. 02:00 on the 8^{th}.

Fig. 5 Radar radial velocity maps

2.3 Diagnostic analysis of key physical quantities From the water vapor flux divergence field at 850 hPa from 08:00 on August 7 to 08:00 on August 8, it can be seen that the water vapor convergence center over Dehong was in the west of Dehong, and the center intensity was the strongest at 08:00 on the 7^{th}, exceeding -6×10^{-6} g/(cm^2 · hPa · s). It remained between -2×10^{-6} and -4×10^{-6} g/(cm^2 · hPa · s) over Mangshi, and there was some water vapor convergence, but it was not the strongest center.

In the specific wet field at 850 hPa, the specific humidity over the entire Dehong was above 14 g/kg from 08:00 on August 7 to 08:00 on August 8, indicating that the low-level water vapor conditions were good. At 20:00 on the 7th, the specific humidity in most parts of Mangshi and southern Ruili increased to more than 16 g/kg, showing that the water vapor over most parts of Mangshi and southern Ruili on the night of the 7th was more abundant, providing sufficient water vapor conditions for the generation of heavy rainfall.

Seen from the radionde map of Tengchong station at 20:00 on August 7, the relative humidity below 300 hPa was basically above 80%, indicating that the atmospheric wet layer was deep, and the wind turned along with the height; there was warm advection, so it was warm cloud precipitation, with high efficiency. In addition, the vertical wind shear in the high and low layers was small, and the guiding airflow in the high layer was weak, which was conducive to the stability and less movement of the precipitation cloud system and echoes, so that the precipitation can be maintained. From 08:00 on the 7th to 08:00 on the 8th, the pseudo equivalent potential temperature of Dehong prefecture was between 350 and 355 K at 850 hPa, indicating that the atmospheric stratification over Dehong was unstable, with high energy and humidity. Besides, the mesoscale convergence line in Mangshi area on the ground map was conducive to triggering convection.

2.4 Analysis of forecasting difficulties For this local heavy precipitation process, it is still very difficult to forecast accurately, especially predict heavy rainstorm, and forecast accurately the falling area of heavy rainstorm. There are mainly the following difficulties in this forecast.

(1) Seen from the stability of the EC fine grid precipitation model, starting from 20:00 on August 6 and 08:00 on August 7, it was predicted that moderate rain and local heavy rain would appear in Mangshi on August 8, and the main rainstorm area in Dehong would be in western Yingjiang and other places. The forecast of rainstorm in the west of Dehong was stable, while there would be no rainstorm in the east.

(2) From the perspective of comparison between multi-model products, the rainfall in the next 24 h was predicted from 08:00 on August 7 and 20:00 on August 7, and based on most of the numerical models and subjective and objective forecasts, it is predicted that small-to-moderate rain would happen in Mangshi, and the local heavy rainfall in Mangshi was about 3 orders of magnitude smaller. Based on the East China model, it was predicted that there were rainstorm spots in the west and east of Dehong, but the predicted magnitude of the process in the whole province based on the model was generally larger. The falling areas of heavy rainstorm were scattered, so it was difficult to judge which areas had high probability, and it had low credibility.

(3) From the analysis of situation field forecast of EC fine grids, it can be seen that the 700 hPa shear line was stable in the Ailao Mountains, and was far away from the prefecture. The southwest airflow at 850 hPa was strengthened on the night of the 7th, but the convergence area was westerly and northerly, and its impact on rainfall in Manshi would not be great. The low-pressure inverted trough at 500 hPa was easterly and northerly, and the predicted wind speed on both sides of the inverted trough was not large, so the low pressure system could not affect Dehong. For the influence of this inverted trough, heavy rain would appear due to the influence of terrain, and the probability of rainstorm and heavy rainstorm was very low in mountainous areas.

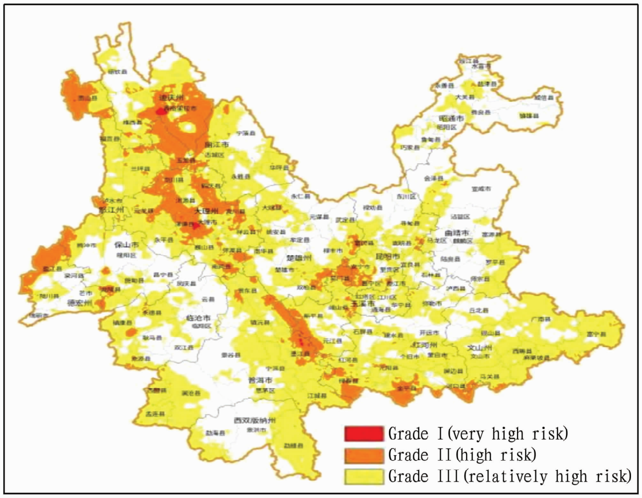
On the afternoon of August 7, the intelligent grid forecast of Yunnan Province predicted that moderate rain would happen in Mangshi in the next 24 h (20:00 – next 20:00). Based on the above analysis, on the afternoon of August 7, Dehong Prefecture Meteorological Observatory predicted that in the next 24 h, moderate rain and local heavy rain would occur in most areas except Yingjiang would suffer moderate-to-heavy rain and local rainstorm, and it was not predicted that single-point rainstorm weather would appear in the east.

3 Decision making and forecast testing

3.1 Forecast and early warning In view of the continuous heavy precipitation process in early August, the Yunnan Meteorological Observatory mentioned in the *Important Weather Forecast* released on August 1 that under the influence of shear lines and warm and humid airflow, it is expected that sustained heavy precipitation would appear in most areas of Yunnan Province from the night of August 1 to August 7, of which the risk of single-point heavy rainstorm in the west of Dehong Prefecture was high. The cumulative rainfall was 60 – 80 mm in most areas, reached 120 – 160 mm in the east of Dehong Prefecture, and exceeded 300 mm in the west of Dehong Prefecture. The process lasted for a long time, and had a wide impact scope and a high risk of rainstorm disaster. It is recommended that relevant areas should strengthen the inspection of disaster hidden points and risk areas, and pay attention to preventing mountain floods, geological disasters, floods of small and medium-sized rivers, and urban and rural waterlogging. From August 1 to 7, the Yunnan Meteorological Observatory issued 15 grade-IV lightning warnings, 1 grade-IV rainstorm warning, and 7 grade-II geological disaster meteorological risk warnings.

Dehong Prefecture Meteorological Observatory made and issued the *Important Weather Forecast* at 16:00 on August 1. It is estimated that heavy precipitation would happen in the whole prefecture from August 3 to 7. Weather forecast in the next 24 h was released at 16:00 on August 6, and it is expected that heavy rain and local rainstorm would occur in Mangshi on August 7, 2023. At 09:00 on August 7, the weather forecast in a week was made and released, and it is predicted that moderate-to-heavy rain and local rainstorm weather would on August 7. Forecast materials were released through official documents, mobile phone short messages, electronic displays, wechat groups, wechat public accounts and other ways.

In terms of meteorological risk warnings, the Yunnan Meteorological Observatory and the Department of Natural Resources of Yunnan Province jointly made and released three geological disaster meteorological risk warning products at 16:00 on August 6, 08:00 on August 7, and 16:00 on August 7, in which it is predicted that the geological disaster meteorological risk of Mangshi in Dehong Prefecture was at grade Ⅲ (high risk) (Fig. 6). In the grade II warning of geological disaster meteorological risk issued at 16:30 on August 7, the meteorological risk of geological disaster in Mangshi was forecast to be grade II (high risk). Dehong Prefecture Meteorological Observatory and Mangshi Meteorological Observatory both issued a grade-II warning of geological disaster meteorological risk on August 7.



Note: It was jointly released by the Department of Natural Resources of Yunnan Province and Yunnan Meteorological Observatory.

Fig. 6 Meteorological risk warning for geological disaster in Yunnan Province from 20:00 on August 7 to 20:00 on August 8 in 2023

3.2 Service situation Before and after the occurrence of the heavy rainfall weather process, the Yunnan Meteorological Observatory issued 2 issues of *Important Weather Forecast*, 7 issues of *Daily Meteorological Report*, 2 issues of *Important Weather Express*, and 25 issues of "1262" *Refined Forecast Topic*. After the release of the *Important Weather Forecast*, it participated in the video conference of Yunnan Emergency Department for flood control and dispatch 5 times, and there were 2 times of temporary dispatch of vice governor Na Yunde.

Dehong Prefecture Meteorological Observatory mainly carried out some meteorological services, including 1 issue of *Weather Weekly*, 1 issue of *Important Weather Forecast*, 3 issues of *Important Weather Express*, 2 issues of *Rainstorm Warnings*, 2 issues of *Meteorological Risk Warnings of Geological Disasters*, 1 issue of *Risk warnings of Mountain Flood Disaster*, 1 issue of *Meteorological Risk Warnings of Roads Highly Affected by Severe Weather in Dehong Prefecture*, and 9 issues of "1262" *Progressive Forecast Service for Heavy Precipitation*. Mangshi Meteorological Observatory released one issue of blue early warning signal for rainstorm, the orange early warning signal for rainstorm at 00:15 on August 8, and one issue of grade-II warning of geological disaster meteorological risk.

3.3 Causes of deviation of heavy precipitation forecast

(1) Seen from the comparison of actual and predicted wind field based on EC fine grids at 08:00 and 20:00 on August 7, the difference between the two was mainly the difference in the position of the 700 hPa shear line. The position of the shear line in the forecast field was westerly, it would mainly affect the west of Dehong, while the actual position of the shear line was easterly.

(2) From the comparison of multi-model precipitation products, the forecast results of precipitation grade in Mangshi on the 8^{th} based on different models were relatively consistent, basically small-to-medium rain, while only CMA-SH9 model predicted rainstorm and heavy rainstorm in the east of Mangshi. The overall forecast grade of CMA-SH9 model is higher, and it often fails to report rainstorm, so its reliability is not high. Therefore, the forecast of rainfall in Mangshi on the 8^{th} did not adopt CMA-SH9 model, mainly using the EC model, and moderate rain was predicted.

(3) Precipitation model products have certain limitations. The test results show that the prediction value of local convection and heavy precipitation weather based on global precipitation model products was smaller. In addition, Dehong Prefecture has complex terrain, and it has a large impact on precipitation. Rainstorm at a single point was prominent. Moreover, there were certain uncertainties in the consideration of topography by model products. Forecasters themselves had insufficient understanding of the triggering effect of complex terrain, and subjective correction was difficult, which was also an important reason for the deviation of heavy precipitation forecast.

4 Conclusions and discussion

(1) The heavy rainfall process was small in scope and prominent in locality, mainly concentrated in the east of Mangshi. It lasted for a long time, and the cumulative rainfall was large. It was mainly stable precipitation, and there was no lightning.

(2) The main impact systems of rainstorm and local heavy rainstorm in Mangshi was as follows: the 500 hPa inverted trough gradually moved westward with the low pressure system to affect Dehong; the 700 hPa shear line remained stable in the southwest, and combined with the convergence and uplift of the lower-level southwest air to provide strong dynamic uplift conditions for heavy precipitation; The southwest airflow over 850 hPa was strengthened and maintained, providing sufficient water vapor transport conditions for the generation and maintenance of heavy precipitation.

(3) The atmospheric stratification over Dehong was unstable stratification with high energy and humidity, while the ground convergence line was maintained in the east, which provided a good triggering condition for the occurrence of heavy precipitation in Mangshi. Moreover, the atmospheric humid layer was deep, and there was warm advection in the lower layer. The vertical wind shear in the upper and low layer was small, and the guiding air in the upper layer was weak, which was conducive to the stability and less movement of the precipitation cloud system and echoes, so that the precipitation could be maintained.

(4) The precipitation echoes were mainly dense stratiform cloud precipitation echoes, and were maintained stably for a long time, so that stable precipitation lasted for a long time in Mangshi. Moreover, there was a convergence area of continuous wind direction and speed and a upwind area in the east of Mangshi, so that the echoes were stable and less moved. The eastern part of Mangshi was blocked by mountains and located on the windward slope.

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Affected by terrain convergence and enhanced dynamic uplift, it was conducive to the continuity and increase of precipitation.

(5) In this process, the forecast of prefecture- and county-level meteorological departments was more accurately, and their services were fine and timely. The warnings had a good time advance. When issuing high-level warnings, the municipal meteorological bureau decisively called relevant departments 6 h and 14 min before the disaster occurred.

(6) Dehong Prefecture has complex terrain, and there were certain uncertainties in the consideration of topography by model products. Forecasters themselves had insufficient understanding of the triggering effect of complex terrain, and subjective correction was difficult, which was also an important reason for the deviation of heavy precipitation forecast. In the future, business personnel should strengthen the research on the influence mechanism of complex terrain on precipitation and the inspection and application of various model products.

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