Analysis of Characteristics of a Heavy Rainstorm Process in Nanchang City on July 7, 2020

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Abstract Based on the conventional observation data, dual polarization radar data and NCEP reanalysis data, the large-scale circulation background field, mesoscale conditions and formation causes of a heavy rainstorm in Nanchang on July 7, 2020 were studied. It was found that this heavy rainstorm occurred under the weather background of the confrontation between the northward air flow behind the trough and the strong southwest warm and humid air flow to the northwest of the subtropical high. The divergence at the upper level, the shear in the middle and low levels, the southward movement of cold air at the low level, unusually abundant water vapor and high unstable energy caused the heavy rainstorm weather. In this process, under the influence of continuous eastward movement of several strong echo cells, an obvious "train effect" was formed in Nanchang, so that the local rainfall was continuous and intense. Moreover, the average of VIL was about 17 kg/m^2, and its variation characteristics were consistent with the variation trend of 5-min rainfall intensity, which had a certain indicator effect on short-term heavy precipitation. The topography of the Meiling Mountain in the west of Nanchang had a great influence on the formation and precipitation distribution of the heavy rain process. There was a strong rainstorm center near the mountain, and the precipitation was obviously larger than that in the plain area.

Key words Short-term heavy precipitation; Mesoscale system; Train effect; Meiling landform
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Nanchang City is located in the north-central part of Jiangxi Province, with Poyang Lake to the northeast and the Meiling Mountains to the northwest, and the Ganjiang River runs through the city from north to south. It has special topographic features. Urban waterlogging and floods occurred frequently in Nanchang City, and especially in the plum rain season short-term heavy rainfall and heavy rainstorm often appear. For instance, the heavy rainstorm from June 14 to 16 in 2011 caused river floods, affecting crops and bringing huge economic losses[1-2]. From June 21 to 22, 2015, the heavy rainfall in Nanchang and its nearby areas resulted in severe waterlogging and affected urban traffic[3]. There are three main reasons for the formation of these floods, including the long duration of precipitation, short-term heavy rainfall, and great impact of complex terrain.

The forecast of heavy rain and short-term heavy precipitation in the plum rain season is always the key and difficult point of weather forecast in Nanchang area. Seen from the physical significance of multi-year forecast, the causes of heavy rainstorm can be roughly divided into the influences of the rapid southward movement of frontal surface, the static front and the strong southwest airflow in the warm zone[4]. There are some analyses on the rainstorm and heavy precipitation in this region, such as an analysis on a single weather process system or a comparative analysis among individual cases[5-8], studies on the regularity of rainstorm process and climate background[9-12], analyses based on satellite and radar characteristics[13-14], and generalization and summarization of mesoscale mechanisms of weather processes[15-16]. The commonality and uniqueness of these rainstorm weather processes coexist, which provides some references for the prediction of rainstorm and short-term heavy precipitation in Jiangxi Province. However, with the deterioration of global climate background and more frequent occurrence of extreme weather, it is very necessary to continue to study the causes and forecasting methods of rainstorm and short-term heavy precipitation.

From July 7 to 8 in 2020, a heavy rainstorm process occurred in the central and northern part of Jiangxi Province. It was strong and wide, and lasted for a long time, which was rare in history. Continuous precipitation in the three stages caused serious flooding in Jiangxi Province, and the largest floods in this century occurred in the Xiuhe River and Raohe River, affecting 1.795 million people in the 6 cities. More than 137 000 people were relocated, and direct economic losses reached 1.24 billion yuan. In order to explore the causes of this extreme rainstorm process, based on conventional meteorological observation data and Nanchang radar data, the circulation situation, convective conditions and mesoscale characteristics of this rainstorm weather process were analyzed, and the phased characteristics of this rainfall and the influence of special terrain were studied to improve the understanding of the occurrence and development of mesoscale convective weather system and provide more reference for the fine forecast of heavy rainstorm.

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1 Actual situation of the weather

As shown in Fig. 1a, from 08:00 on July 7 to 08:00 on July 8 in 2020, a heavy rainstorm appeared in Nanchang City, and there was an extremely heavy rainstorm in some areas. Large-scale waterlogging appeared in the urban area, and over-warning water level can be found in some areas. The average precipitation in the city was 116.3 mm. The precipitation was more than 100 mm in 77 stations and more than 250 mm in 6 stations. Within the municipal district, the precipitation in Wanli No. 1 Middle School station was the largest, up to 268.4 mm, followed by Banling station in Wanli District (255.4 mm). During this process, the short-time rain intensity, daily precipitation and heavy rainstorm range all reached a record high.

The precipitation process began in the afternoon. From 13:00 to 14:00 on July 7, convectional clouds formed in Jing'an County, Yichun City, and quickly developed cloud cluster with precipitation of more than 10 mm/h. After 15:00, the cloud cluster developed rapidly, and slowly moved to the west, while the hourly rainfall increased significantly. Seen from the hourly precipitation in Nanchang station, Xinjian station and Wanli No. 1 Middle School station shown in Fig. 1b, heavy precipitation mainly occurred from 16:00 on July 7 to 02:00 on July 8. From 16:00 onwards, heavy precipitation over 30 mm/h happened from Anyi County to Xinjian District, and the maximum hourly precipitation in Wanli No. 1 Middle School station was up to 56.2 mm/h. The main rainfall area remained stable over Nanchang until 02:00 on July 8.

2 Circulation background and characteristics of rainstorm environment field

2.1 Circulation background At 500 hPa on 08:00 on July 7, there was a trough and ridge in the middle and high latitudes in the northern hemisphere, and North China was controlled by the East Asian trough. The longitude of the circulation was large, and the northerly air flow behind the trough led the cold air move to the south. As shown in Fig. 2a, the low-latitude area was controlled by the subtropical high, and the 588 line traversed the central and northern parts of Jiangxi Province. Strong southwest warm and humid air was constantly transported the area near 29° N to the northwest of the subtropical high, and the high-altitude northward cold air at 200 hPa was transported to the south. The warm and cold air met in the central and northern parts of Jiangxi Province to the north of the subtropical high. The large circulation background was very conducive to the generation and maintenance of rainstorm.

This process included convective precipitation on the south side of the frontal rain belt and the southward movement of the frontal rain belt in the later period. The 588 line at 50 hPa was located in the north of Jiangxi Province at 08:00 on July 7, and the northern cold air at 200 hPa had an obvious diverting area in the north of Jiangxi Province. The precipitation area was located to the north of the Western Pacific subtropical high. After 20:00, the subtropical high gradually retreated to the east, and the rainfall area then moved to the south. The shear line at 700 hPa was located in the Jianghuai line, and the shear line moved slowly. There was a 12 m/s jet stream to the south of the shear line, and there was convergence of wind direction and wind speed in the north of Jiangxi. The wind speed increased by 20:00, and the convergence of wind speed was located in the north of Jiangxi. In Fig. 2b, the specific humidity at 850 hPa reached 17 – 18 g/kg at 08:00 on July 7, higher than that of daily rainstorm (14 g/kg). As shown in Fig. 2c, the shear line at 925 hPa was located in the north of Jiangxi Province, and there was a low-level jet stream. The temperature frontal zone was dense, and there was a warm ridge extending eastwards. There was a quasi-stationary front on the ground (Fig. 2d). The combination of unusually sufficient water vapor and cold air provided dynamic and water vapor conditions for the occurrence of heavy rainstorm. The strong low-level convergence accelerated the vertical rise, and the warm and moist air in the atmosphere was lifted, making the precipitation intensified and sustained.

2.2 Analysis of water vapor and thermal conditions From Fig. 3a, it can be seen that at 14:00 on July 7, there existed a large value area of water vapor flux in an east – west direction in the water vapor flux field in the middle and low levels, extending from the Yunnan – Guizhou Plateau to Jiangxi through Hunan. Its central axis passed through the northern part of Jiangxi, and there was a narrow water vapor transport channel on the northern side of the jet until 08:00 on July 8 (Fig. 3b). The high-value area of water vapor flux was mainly concentrated in this region. Meanwhile, at 700 hPa, a high-value zone of water vapor flux of 18 – 20 g/(cm · hPa · s) appeared in Nanchang area from 14:00 on July 7 to 08:00 on July 8, but it was larger than the average of 16 g/(cm · hPa · s) during the flood season. In the whole process, the water vapor high-value axis was located in the north of Jiangxi, and the position was consistent with the low-level jet stream.

Potential pseudo-equivalent temperature (θ_{se}) represents the comprehensive characteristic quantity of temperature, pressure and humidity in the atmosphere, and its distribution reflects the distribution of energy. When the horizontal gradient of θ_{se} in the lower layer was large enough, there was a strong horizontal energy frontal zone, which was conducive to the occurrence and development of strong convective weather. At 14:00, there was an obvious energy frontal zone at 1 000 hPa, and the strong convective weather occurred near the θ_{se} frontal zone (Fig. 4). The θ_{se} near the frontal zone ranged from 344 to 360 K, and the θ_{se} difference between the north and south three latitudes was about 16 K. The distribution was similar at 925 – 850 hPa. From the vertical profile, at 14:00, $\theta_{se}/z < 0$, and it was in a convective unstable state. There was a clear cold center near 30° N, and the frontal surface also extended into the vicinity of 29° N. Seen from the vertical distribution of meridional wind, the downdraft behind the cold center and the updraft in front of the cold center formed a vertical circulation circle, and the uplift of the frontal zone was significant. It can be said that in this process, the intrusion of cold air in the boundary layer was one of the important reasons for producing short-term heavy precipitation, and the rise of the frontal surface provided a certain convective triggering mechanism.

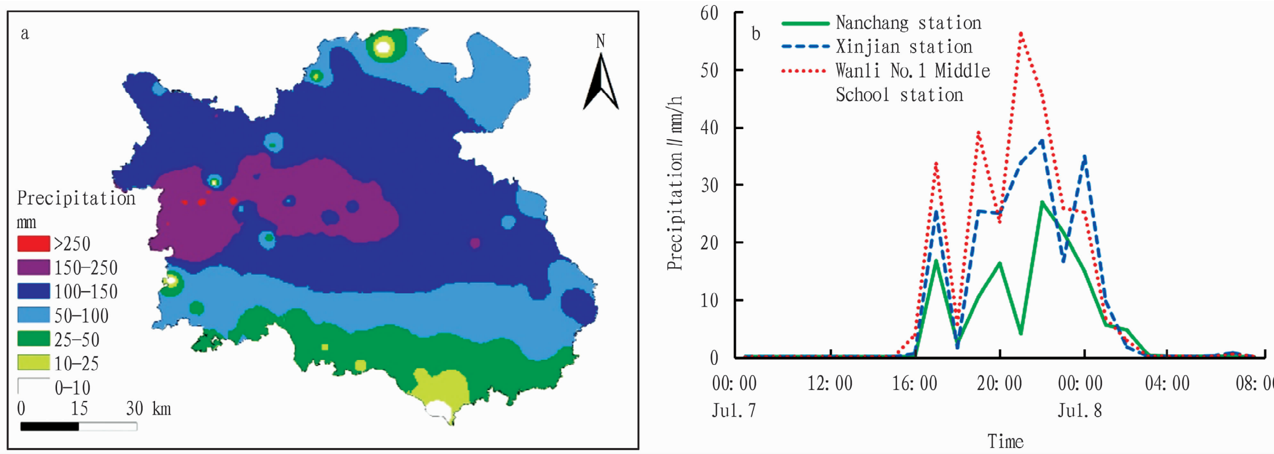


Fig. 1 Spatial distribution of precipitation in Nanchang City (a) and changes of hourly precipitation in Nanchang station, Xinjian station and Wanli No. 1 Middle School station (b) from 08:00 on July 7 to 08:00 on July 8 in 2020

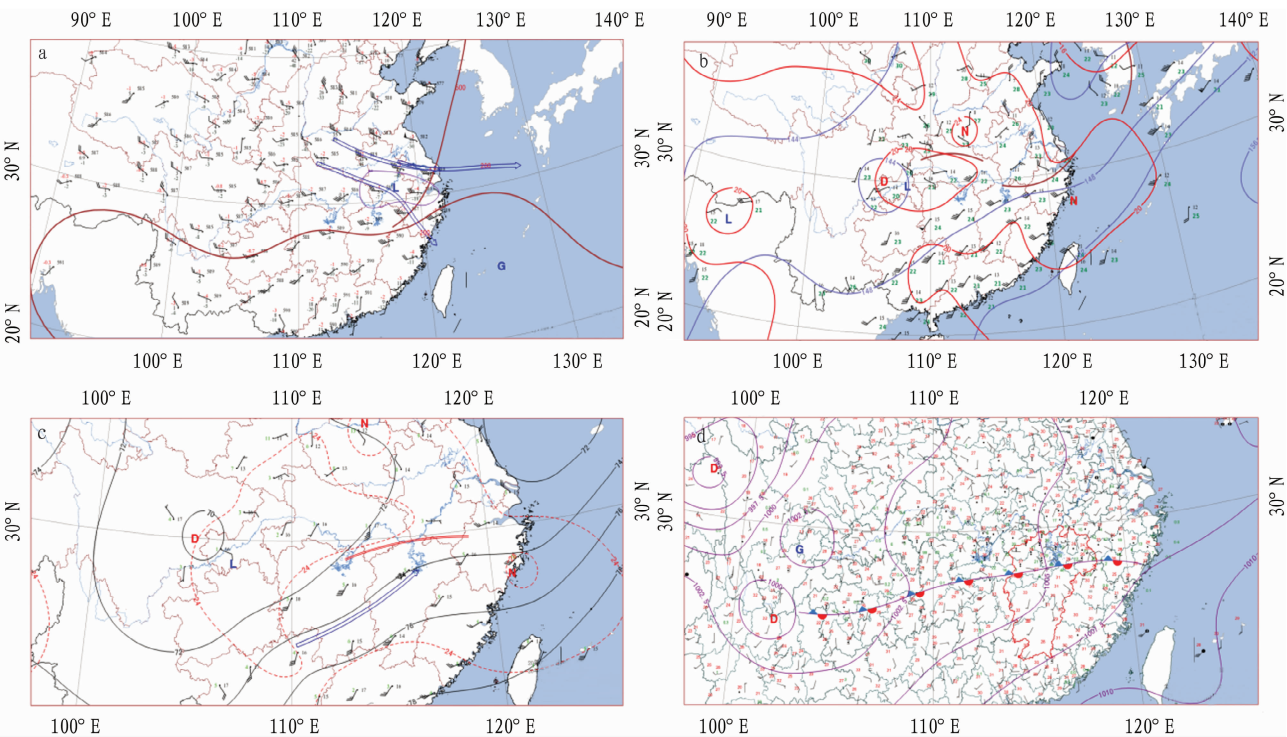


Fig. 2 Circulation pattern at 500 hPa (a), 850 hPa (b), and 925 hPa (c) and on the ground (d) at 08:00 on July 7, 2020

2.3 Triggering mechanisms The upward motion near the convergence line in the boundary layer was strong, which was often an important triggering mechanism of strong convective weather[17]. In the first stage of this process, there was obvious convective properties, and the range was small. Convection began to trigger on the west side of Anyi, and then gradually moved eastwards, forming a train effect. It moved and strengthened along the ground convergence line. From the perspective of dynamic mechanism, Nanchang area was controlled by the subtropical high, and the pulsation in the jet stream was not clear. Therefore, the existence of the ground dynamic system was particularly important for the triggering effect of convective precipitation. As shown in the wind field of the automatic ground station from 12:00 to 14:00 in Fig. 5a, there was already an obvious ground convergence line at 12:00 on July 7, namely the convergence of southwest wind and northeast wind. The triggering effect of this convergence system with opposite wind direction was particularly strong. The ground convergence line always existed and slowly moved to the southeast. From the position of the convergence line corresponding to the precipitation echo, the convergence line was located at the back of the linear echo. Under the condition that the triggering system was stable and less moving, the heavy precipitation continuously generated and moved to the northeast along the basic air flow in the upper air, which was conducive to the emergence of short-term heavy precipitation.

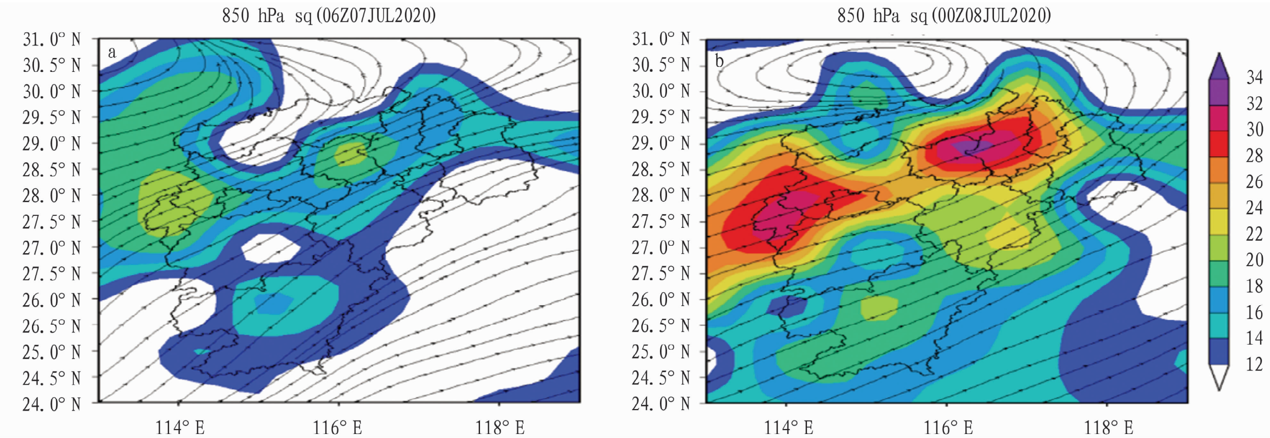
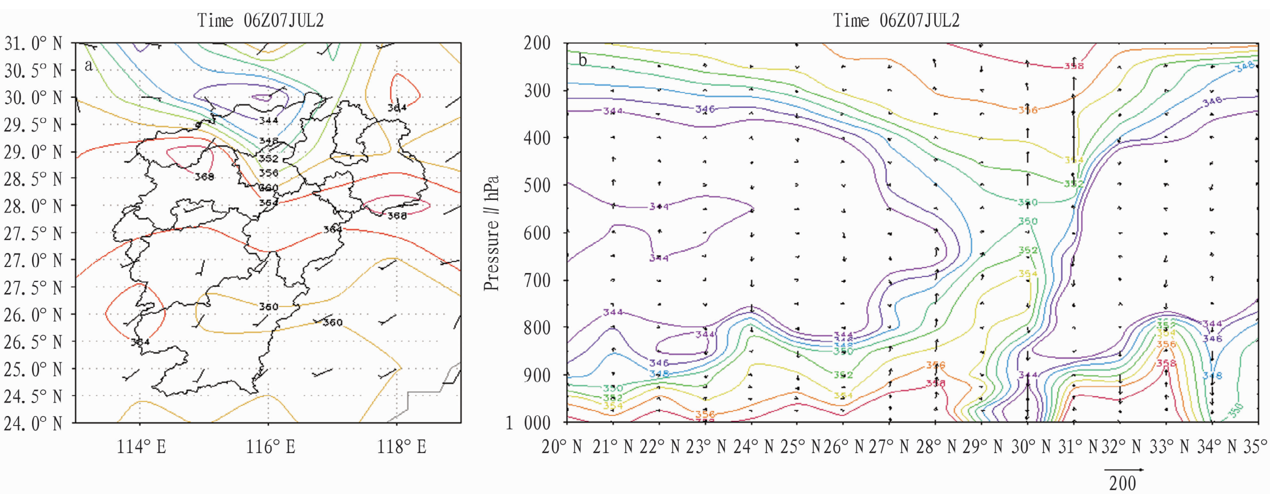


Fig. 3 Water vapor flux at 14:00 on July 7 (a) and 08:00 on July 8 (b)



Note: The vector line was the vector synthesis of v and $\omega\times100$, and the solid line was the pseudo-equivalent potential temperature contour.

Fig. 4 Distribution of potential pseudo-equivalent temperature at 14:00 on July 7 (a) and vertical profile of potential pseudo-equivalent temperature along 115.92° E (b)

In the second stage, with the development of the convective system, the environmental field in Nanchang area changed. The intrusion of cold air in the middle and low levels deepened the vertical circulation, so that the dry and cold air in the middle and high levels was involved faster, and the main shear rain belt moved southwards faster to a certain extent. In addition, the subtropical high slowly receded to the east, and the shear line moved southwards gradually. At the same time, there was a flow diverging zone at 200 hPa, and there was obvious divergence, so new convective cloud clusters were constantly generated backward. In addition, because the air flow was from southwest to northeast, the convective cells continued to spread eastwards, forming a train effect. Under the joint action of these factors, the whole rain belt was maintained for a long time.

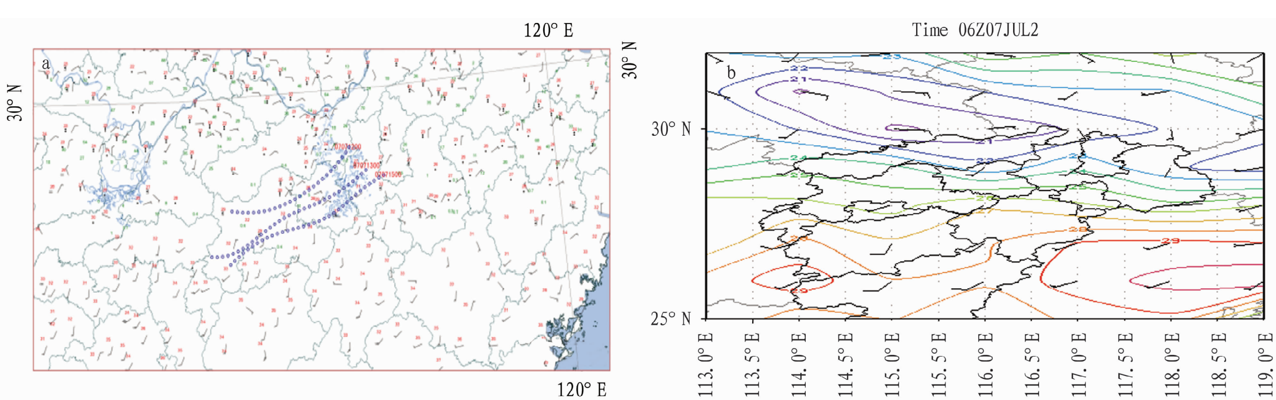


Fig. 5 Ground convergence line from 12:00 to 15:00 in the automatic ground station (a) and temperature field at 925 hPa (b)

From the distribution of temperature field and wind field in Fig. 5b, it can be seen that there was the ultra-low level jet stream on the south side of the quasi-static shear line in the wind field at 925 hPa, and the 23 ℃ temperature frontal zone had affected the northwest of Jiangxi. It indicates that the cold air in the boundary layer began to affect Nanchang along the lower interface of the frontal surface, and converged with the warm and wet air near 29.5° N, forming a convergence center. Meanwhile, there was a vertical frontal circulation accompanied by low-level convergence. In the temperature field, there was an obvious temperature frontal zone at 925 hPa, with a large gradient, which strengthened the formation of ground convergence and provided a triggering mechanism for convective weather.

3 Analysis of mesoscale features

3.1 Study of radiosonde revision From the environmental sounding variables shown in Table 1, it can be seen that during the precipitation process, the humidity of the low and middle layer over Nanchang was relatively large, and there was moderate wind shear in the vertical direction (925 – 700 hPa). Lifting condensation level (LCL) indicates that the height from the warm cloud base to 0 ℃ layer (ZH) was thicker. Before the process began, the convective available potential energy (CAPE) over northern Jiangxi was >700 J/kg, KI index >40, and SI index <0. The atmosphere was in an unstable state, and the level of free convection (LFC) expressed in atmospheric pressure was approximately at 810 hPa. Especially after the correction, CAPE increased rapidly indicating that the environmental conditions were good, and the convection was easily triggered. At 0 – 6 km, wind shear reached 13 – 16 m/s, which was similar to the threshold of vertical wind shear in rainstorm environment. The vertical wind shear showed an increasing trend, which was conducive to forced uplift and convective strengthening. Besides, KI index also first increased and then decreased, also meaning that the water vapor content was high, and the low-level jet stream disturbance was obvious to a certain extent, so it had a significant indicator significance for the occurrence of heavy precipitation.

Table 1 Environmental sounding variables

Time	CAPE//J/kg	KI	SI	PLFC//hPa	PLCL//hPa	Wind shear at 0 – 6 km//m/s	ZH//m
08:00 on July 7	786.6	39.3	0.15	819.2	951.2	13.1	5 222
20:00 on July 7	112.7	41.9	–1.88	806.1	996.1	16.0	5 335
08:00 on July 8	509.6	38.6	0.43	819.3	993.3	8.0	5 224

According to the microphysical theory of clouds, the thicker the warm clouds in the precipitation system, the more conducive to the generation of high-precipitation efficiency. The thickness of the warm clouds was estimated according to the thickness between the uplifting condensation height and the melting layer. From the data of Nanchang sounding station, it can be seen that from 08:00 to 20:00 on July 7, the lifting condensation height decreased from 951 to 996 hPa, and the 0 ℃ layer height increased from 5 222 m to 5 335 m. Due to the increase in the thickness of warm clouds, precipitation efficiency enhanced, which was one of the important reasons for the heavy precipitation.

3.2 Characteristics of radar echoes As can be seen from the evolution process of radar echoes (the figure is omitted), since 13:00 on July 7, scattered stratospheric mixed precipitation echoes appeared in the west of Nanchang City, and slowly moved eastwards. After 14:00, under the strong southwest jet, a number of strong convective echo cells arranged into linear convective cloud echoes in the southwest of Nanchang City, and continued to advance eastwards, producing local heavy precipitation. At 15:00, a number of strong convective echo cells were close to each other, forming a slanted "一"-shaped echo, forming a narrow-band northeastern-southwest heavy precipitation echo in the south of Jiujiang, the northwest of Nanchang and the east of Yichun. By 16:00, the previous banding strong precipitation had already swept over Nanchang City, but a new linear echo appeared over Nanchang again, and tended to be stable. The strong echo cell on the west side moved eastwards and merged with it, tending to form a flake strong echo area. From 17:00 on July 7 to 00:00 on July 8, a large area of echoes over the Jianghuai River basin in the north of Jiangxi Province moved southwards, and merged with the flake strong echoes generated here, so a large area of strong echoes had been maintained over Nanchang City, resulting in continuous and intense precipitation. After 01:00, the echoes gradually moved eastwards, and the precipitation in Nanchang City gradually decreased from west to east.

In this process, echoes began to appear on the west side of Nanchang, and then strengthened rapidly during the eastward movement. The convective characteristics were obvious, and the range of echoes with the intensity of >45 dBZ also gradually expanded. From 16:00 to 23:00, Nanchang was affected by the continuous eastward movement of several strong echo cells, and strong echoes with intensity of more than 50 dBZ continuously passed through, forming an obvious "train effect". As a result, the precipitation in Nanchang is long in time and strong in intensity.

As can be seen from the radar echo (Fig. 6a) at the time of heavy precipitation at 20:39, the intensity of the echoes was greater than 60 dBZ, and the precipitation was long in time and strong in intensity. Seen from the differential reflectivity factor (ZDR) in Fig. 6b, ZDR > 3, showing that the precipitation particles here were ellipsoidal and large in diameter. Meanwhile, the specific differential phase (KDP) is shown in Fig. 6c, KDP > 3 indicates that there was more liquid water. It can be inferred that the precipitation raindrops were large and dense at this time. Seen from the radar profile in Fig. 6d, the height of strong echoes with the intensity of more than 45 dBZ was basically no more than 6 km, and the extending height of the strong core larger than 50 dBZ was about 4 – 5 km. The overall precipitation echo had a low centroid and strong echo intensity, belonging to the characteristics of heavy precipitation echoes. Compared with the actual rainfall, it was found that the above strong echoes produced short-term heavy precipitation with intensity of of 56 mm/h near Wanli area.

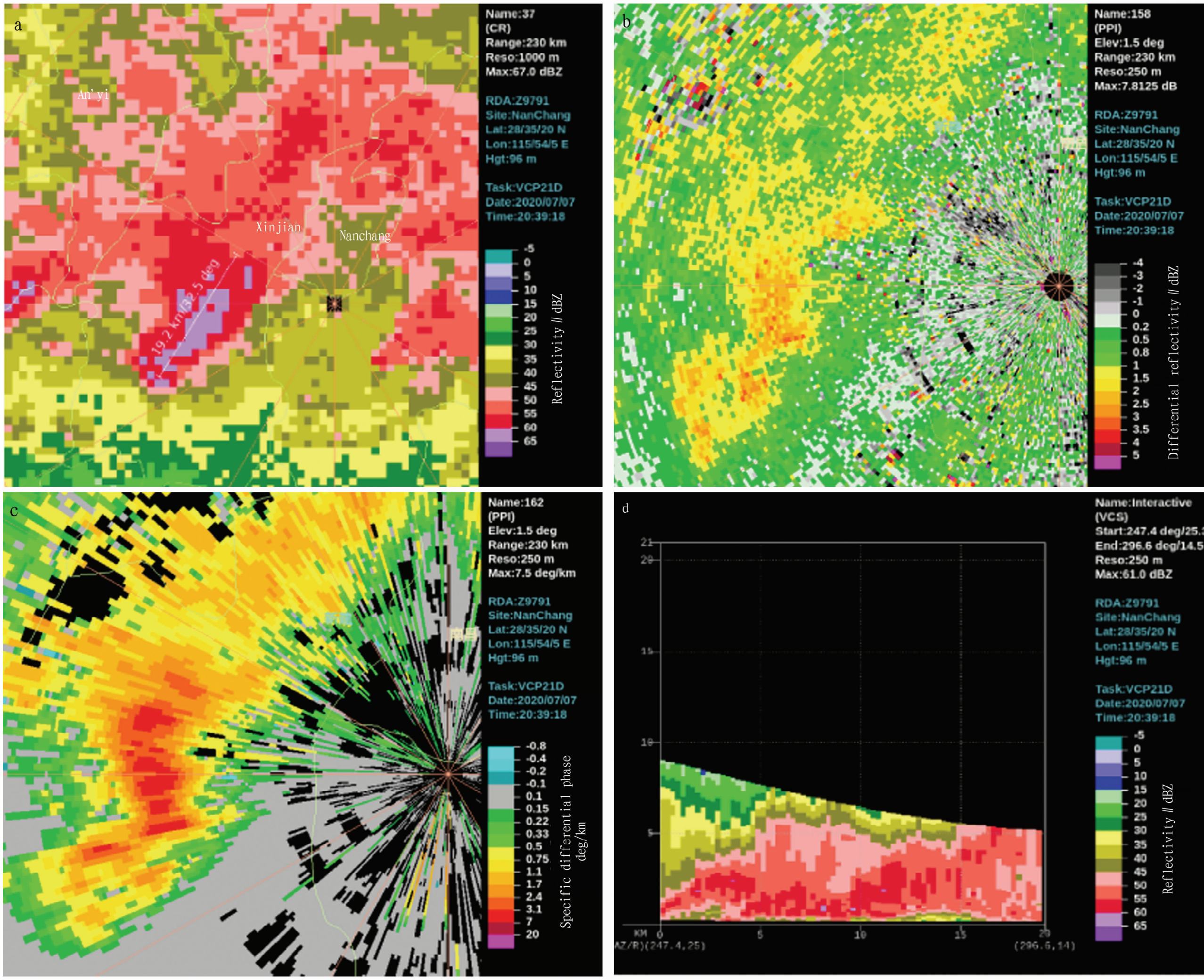


Fig. 6 Dual polarization radar combined reflectivity (a), dual polarization radar differential reflectivity factor (b), dual polarization radar specific differential phase (c), and strong echo profile (d) at 20:39 on July 7

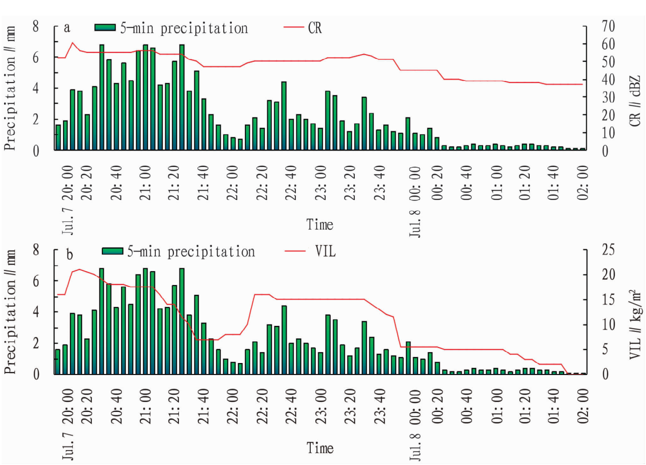


Fig. 7 Changes of 5-min precipitation, CR (a) and VIL (b) from 20:00 on July 7 to 02:00 on July 8 in Wanli No. 1 Middle School station

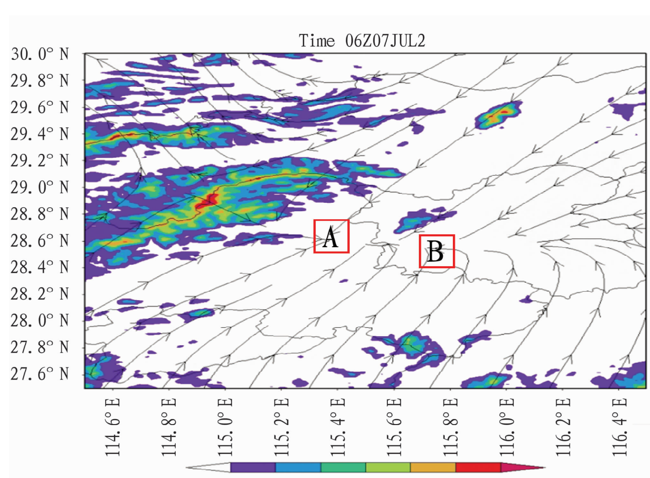


Fig. 8 Superposition chart of the 1 000 hPa wind field and terrain at 14:00 on July 7

3.3 Analysis of topographic effect In the process of this heavy rainstorm, the topography of Meiling mountainous area in the west of Nanchang City also played a great role in the formation of this disaster-causing heavy rainstorm and the distribution of precipitation. Since there are often 35 – 50 km systems in the boundary layer in mountainous areas, most of which are vorticity, and there are also some convergence lines, their development and evolution are closely related to precipitation. Fig. 8 shows the superposition of the 1 000 hPa wind field and terrain during the heavy rainstorm at 14:00 on July 7. Areas A and B had the strongest precipitation and the strongest convergence of the low-level air flow. Area A was the windward slope in the south of the Meiling Mountain, showing a trumpet shape. On the one hand, the windward slope can strengthen the lifting of warm and wet air; on the other hand, the topography of the trumpet was also conducive to the occurrence and development of small and medium-sized atmospheric disturbance, which was a favorable condition for the generation of rainstorm. It can also be seen from the figure that there was an obvious convergence of southerly and northerly air flow in this area. This disturbance of topographic convergence in front of mountains led to the disturbance of boundary layer, which was one of the power sources causing the rainstorm. Area B was located in the valley of Meiling. There were thermal and mountain blocking forcing in the valley, so that the southerly warm and wet air was maintained here, so there was also strong precipitation here. Continuing to the east, the mountainous terrain gradually disappeared, and precipitation decreased. Hence, the topography of Meiling had a very obvious effect on the rainstorm process, and the precipitation in the mountains was obviously larger than that in the plain area. At the same time, Poyang Lake is located just to the east of Nanchang. After the easterly airflow blew over the lake at night, relatively warm and moist air would be transported to Nanchang, which strengthened the intensity and continuation of precipitation in Nanchang to a certain extent.

Fig. 7a shows the 5-min precipitation and combined reflectivity (CR) of Wanli No. 1 Middle School station during the strongest precipitation period from 20:00 on July 7 to 02:00 on July 8. It can be seen that the 5-minute precipitation varied greatly from 20:00 to 23:00, indicating that the precipitation was mainly convective precipitation. The change of CR was not obvious, and the maximum echo intensity in the process of heavy precipitation was basically >45 dBZ, but when the echo intensity was >50 dBZ, 5-min precipitation was greater than 10 mm. When CR changed, 5-min precipitation also changed roughly. Therefore, the change of CR had a certain reference value for the change of 5-min precipitation on the ground, but the prediction was not obvious. However, it is worth noting that vertically integrated liquid (VIL) had a good correspondence with the change of 5-min rainfall intensity. It can be found from Fig. 7b that VIL changed significantly during the process of heavy precipitation, and its attenuation or enhancement were more consistent with the trend of 5-min precipitation. VIL changed 5 – 10 min earlier than the precipitation. Therefore, the change of VIL was a good indicator for the pure liquid heavy precipitation with fewer mixed particles.

4 Conclusions

Starting from the analysis of weather situation, combined with thermal and dynamic conditions, the corresponding relationship between the system configuration of each layer and rainfall falling areas was mainly analyzed, and the characteristics of different stages of the heavy rainstorm process were analyzed to find the favorable conditions that caused the occurrence of local heavy precipitation, so as to provide technical reference for the fine forecast of severe convective weather with obvious local characteristics.

(1) The heavy rainstorm occurred under the weather background that the northerly air flow behind the trough confronted the strong southwest warm and wet air flow on the northwest side of the subtropical high. In Nanchang, there was divergence in the upper level, shear in the middle and lower levels, and quasi-stationary front on the ground. The strong low-level convergence accelerated the vertical rise, so that the warm and moist air in the atmosphere was lifted and combined with the cold air, which enhanced the dynamic and water vapor conditions for the occurrence of heavy rainstorm.

(2) The water vapor condition in Nanchang area was good, and the process was always in the high-value zone of water vapor flux, with the specific humidity of 17 g/kg, far beyond the water vapor indicator of general rainstorm. In the whole process, the convection conditions were good, and the gradient of the pseudo equivalent temperature front was large. The vertical section shows the vertical circulation generated by the convective process, and there was also cold air intrusion at the lower level, which was more conducive to the convective triggering.

(3) In this process, Nanchang was affected by the continuous eastward movement of several strong echo cells, and strong echoes with the intensity of more than 50 dBZ continued to pass through the city, forming an obvious "train effect", which made the local rainfall violent and lasting. Dual-polarization products also showed the raindrop shape of precipitation better. In addition, the average of VIL was about 17 kg/m^2, which was consistent with the trend of hourly precipitation. VIL was 5 – 10 min ahead of the precipitation. The change of VIL had a good indication for such precipitation with fewer mixed particles.

(4) The topography of the Meiling Mountain in the west of Nanchang had a great influence on the formation and precipitation distribution of this heavy rainstorm process. The central area of large values in the precipitation process was located in the Meiling area of Nanchang, and the large-value area was located in the valley, windward slope and leeward slope (the direction of the system movement). The rainfall near the mountainous area was significantly larger than that in the plain area.

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the geostrophic deviation wind and aggravating the development of strong sandstorms. A cold front moved southeastwards on the ground. There was a large 3-h positive variation of pressure behind the front, and the barotropic wind was strong.

6 Conclusions

(1) The dust weather was a cold front type strong sandstorm process, and the main body of dust entered Ulanqab City from the central part of Inner Mongolia, and moved from the northwest to the southeast, resulting in a large range of dust weather in the north.

(2) The invasion of surface cold front was an important dynamic mechanism of sandstorm outbreak. When the visibility plummeted, the wind direction changed from southwest to northwest. The wind force first dropped and then rose, so the temperature plummeted. As the main body of cold high pressure affected our city after the transit of cold front, the wind force declined, and the dust weather basically ended.

(3) Downward transmission of upper-level wind momentum was the main reason for the development of dust weather. In the early stage, strong cold air accumulated in West Siberia. When the transverse trough turned to be vertical, the cold air moved rapidly eastwards along the westerly jet with the cold trough or the small trough in front of it. The subsidence motion combined with high-altitude convergence and low-altitude divergence made the high-altitude wind momentum pass down, and the near-surface wind increased, forming a strong frontal zone with a lot of wind and sand.

(4) Before the emergence of strong sandstorms, on the 500 hPa upper chart, there was a high-pressure ridge over the Ural Mountains or its west side, while a deep cold trough was formed in West Siberia, and a circulation pattern of a trough and ridge was formed in the middle and high latitudes of Eurasia.

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