Analysis of a Rainstorm to Heavy Rainstorm Process in Fuxin City in 2024

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Abstract Based on conventional meteorological observation data, radar data, satellite cloud images, microwave radiometers and other data, a rainstorm to heavy rainstorm process in Fuxin from August 19 to 21, 2024 was analyzed from aspects of precipitation conditions, circulation patterns, water vapor conditions, dynamic characteristics, and evolution of small-scale systems. The results show that during this precipitation process, the subtropical high was northward and stable. The low vortex moved eastward and northward along the edge of the subtropical high. The blocking high and the cut-off low vortex system were deep, and a short-wave trough formed in the middle latitudes. Cold air moved eastward to continuously converge with warm and humid air currents from the northwest side of the subtropical high over Fuxin. The low-level jet stream guided the moisture from the periphery of the subtropical high to be transported to Liaoning, and a water vapor convergence center formed in Fuxin. The upward movement was intense, which was conducive to the occurrence of heavy precipitation. As the system continued to develop, the low-level water vapor convergence center gradually extended to the upper and middle levels, providing the necessary water vapor conditions for the rainstorm. The strengthening and maintenance of positive vorticity in the middle and lower levels were the result of the coupling effect between the low vortex and the low-level jet stream. The mesoscale and small-scale convective systems all had the characteristic of backward propagation. In the early stage of the convection, the updraft movement was strong. On the infrared cloud image, TBB decreased significantly, and the cloud top height rose obviously. As the convective system developed, the newly formed convective cells merged with the mature cells, so that rainstorm cloud clusters continuously developed. The strong echo center was low, and the precipitation efficiency was high. Under the effect of the train effect, a continuous rainstorm process occurred in Fuxin. With the increase of atmospheric water vapor and liquid water content, short-term heavy precipitation appeared. At the same time, the changing trend of water vapor derived by microwave radiometer inversion was relatively consistent with that of precipitation. The continuous transportation of water vapor was a necessary condition for the occurrence of the rainstorm.

Key words Rainstorm; Precipitation; Fuxin

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From August 19 to 21, 2024, a rainstorm to heavy rainstorm process happened in Fuxin City. Different from the rainstorms in Sichuan, Guizhou, Hunan, Fujian, and other areas[1-6], this precipitation event had extreme characteristics such as large cumulative rainfall, strong short-term rainfall intensity, wide influence area, and long duration. Some areas of Fuxin City coincided with the previous concentrated rainfall areas, resulting in urban flooding, farmland waterlogging, geological disasters, *etc*. Meanwhile, the water level of three reservoirs exceeded the flood limit. Temporary waterlogging occurred in the urban area, and some roads were temporarily closed and controlled. 19 river-related hydraulic facilities were damaged, and some rural roads were damaged. A total of 615 people were evacuated throughout the city. To deeply understand the occurrence and development mechanism of this strong precipitation event and improve the forecasting and warning capabilities for such extreme rainstorms, the precipitation conditions, circulation patterns, water vapor conditions, dynamic characteristics, and evolution of small-scale systems during this event were analyzed based on conventional meteorological observation data, radar data, satellite cloud images, microwave radiometers and other data, aiming to provide reference for the forecasting, warning, and disaster prevention and mitigation of similar rainstorm events in Fuxin City.

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1 Analysis of the precipitation situation

From August 19 to 21 in 2024, a widespread and persistent heavy precipitation event occurred in Fuxin. The precipitation began in the morning of August 19 and ended on the night of August 21. There was a local heavy rainstorm on August 20 and local rainstorms on August 19 and 21.

This precipitation process was divided into three stages: in the afternoon of August 19, rainstorms occurred in 2 towns; from the daytime to the night of August 20, heavy rainstorms happened in 7 towns; in the afternoon of August 21, rainstorms appeared in 3 towns. The average precipitation during this process was 69.0 mm, and the maximum precipitation (165.4 mm) occurred in Wofenggou Village, Fuxin County. Cumulative precipitation was 50.0-99.9 mm at 37 stations and 100.0-199.9 mm at 17 stations. The heavy rainfall was concentrated from 06:00 to 09:00 and from 17:00 to 24:00 on August 20. The maximum rainfall was up to 91.2 mm on August 19, 120.0 mm on August 20, and 73.2 mm on August 21.

During this process, a total of 43 stations experienced short-term heavy precipitation, among which hourly rainfall intensity exceeded 40 mm/h at 9 stations. The maximum hourly rainfall intensity reached 80.2 mm/h, occurring in Jiamusu Village, Taiping Town, Fuxin County (ranked 3rd in history), followed by Qingquan Reservoir in Zhangwu County (65.5 mm/h) and Fosi Town, Fuxin County (57.3 mm/h).

2 Analysis of circulation pattern characteristics

At 08:00 on August 19, 2024, the meridional extent was large in the middle and high latitudes of Eurasia at 500 hPa; there was high pressure ridges over the northeast of Lake Baikal and the northwest of the Sea of Japan, and cyclonic circulation over Hetao region; the subtropical high was divided into two centers by a low vortex. At 850 hPa, there was high-pressure circulation in the northeast of Inner Mongolia and a southerly wind at the bottom. The northerly wind in Hebei and the southwest wind behind the subtropical high formed two shear lines in the north – south direction. The configuration of the upper and lower air masses was a retrograde situation. At 08:00 on August 20, the eastern part of the subtropical high and the continental high were connected to form a high-pressure dam. It gradually extended westward and rose northward. A cut-off low vortex formed in Hetao region, and due to the obstruction of the western part of the subtropical high, it rotated and turned in place. At 20:00 on August 20, the continental high ridge and the subtropical high moved eastward, while the low vortex in Hetao region moved eastward and northward and gradually weakened. Cold air spread eastward and moved southward in the rear part of the cut-off low vortex, while short-wave troughs formed, deepened and moved eastward in the mid-latitudes. The southwesterly jet stream and the southerly air flow around the subtropical high continuously transported warm and humid moisture, and a distinct water vapor convergence center formed in the southwest of Liaoning. Heavy to torrential rain occurred in the left front of the low-level jet stream. At 08:00 on August 21, as the high-pressure ridge moved eastward, the low vortex over North China moved eastward and northward to the central eastern part of Inner Mongolia, and the head of the jet stream reached the northeastern region, so the precipitation intensity weakened. At 08:00 on August 22, the low trough moved eastward and rose northward; the subtropical high moved eastward and southward, so the precipitation gradually came to an end. The ground was controlled by the top of the Jianghuai cyclone trough, and there was no obvious influence of cold air.

3 Diagnosis analysis of physical quantities

3.1 Water vapor conditions From the water vapor flux divergence at 850 hPa at 02:00 on August 22 (Fig. 1a), it can be seen that the southwest low-level jet and the southeast jet around the subtropical high transported water vapor to Fuxin, resulting in a significant increase in the water vapor flux in the south of Fuxin. The easterly wind at the bottom of the high-pressure circulation in the northeast of Inner Mongolia and the southwest wind behind the subtropical high formed clear convergence, which was conducive to the occurrence of heavy precipitation in Fuxin. The time – height vertical section diagram of water vapor flux divergence at Fuxin station (Fig. 1b) shows that before August 20, water vapor was mainly concentrated below 850 hPa. With the continuous transportation of water vapor from the periphery of the subtropical high, the water vapor convergence zone significantly strengthened after 14:00 on August 20, even reaching around 600 hPa. However, the strong convergence center was located below 850 hPa, and the center strength was up to -22×10^{-6} g/(s · hPa · cm), indicating that the contribution of the low-level jet to water vapor transport was significant. After 02:00 on August 21, the low-level water vapor significantly increased, and the height remained the same, but the low-level center strength was above -23×10^{-6} g/(s · hPa · cm). It can be seen that the continuous water vapor transport and strong water vapor convergence effect provided necessary water vapor conditions for the rainstorm. After 08:00 on August 21, the low-level water vapor convergence significantly weakened, and the precipitation intensity decreased.

3.2 Dynamic conditions Fig. 2 shows that as the low-level jet stream strengthened and the low vortex developed, due to the influence of the eastward movement of the low-pressure system, the positive vorticity advection near 200 hPa was significant during the precipitation period, which caused high-altitude dispersion, intensified the upward movement of warm air, and promoted the development of the ground system. As shown in Fig. 2a, the positive vorticity center extended to 500 hPa on August 19, and the lower-level positive vorticity center was 11×10^{-4} s^{-1}. As the system developed, the lower-level vorticity significantly increased after 08:00 on August 20, and reached the maximum at 02:00 on August 21. The central value at 925 – 850 hPa was 23×10^{-4} s^{-1}. The height of positive vorticity in the middle and lower troposphere coincided with the strongest precipitation period of the rainstorm center, revealing that the strengthening and maintenance of the positive vorticity in the middle and lower levels is the result of the coupling effect of the low vortex and low-level jet stream. From the divergence plot (Fig. 2b), it can be seen that a clear negative-value area was present at the lower level since 08:00 on August 19; the negative-value area of lower-level divergence significantly expanded around 02:00 on August 21, and the divergence center reached above -16×10^{-4} s^{-1}, corresponding to a significant convergence center in the upper level. The maximum convergence center at 500 hPa was 23×10^{-4} s^{-1}, and the upper-level divergence area was superimposed above the lower-level convergence area. This configuration was conducive to the occurrence and maintenance of strong precipitation.

4 Development and evolution of small-scale systems

4.1 Analysis of radar data The radar of Yingkou shows that from 10:00 to 11:00 on August 19, scattered convective storms emerged in Beipiao, Yixian, and Huludao, and were influenced by the low-level southwest wind. The echoes gradually developed from south to north. At 12:14, they strengthened into strong convective cells in Qinghemen District, Fuxin, and the central reflec-

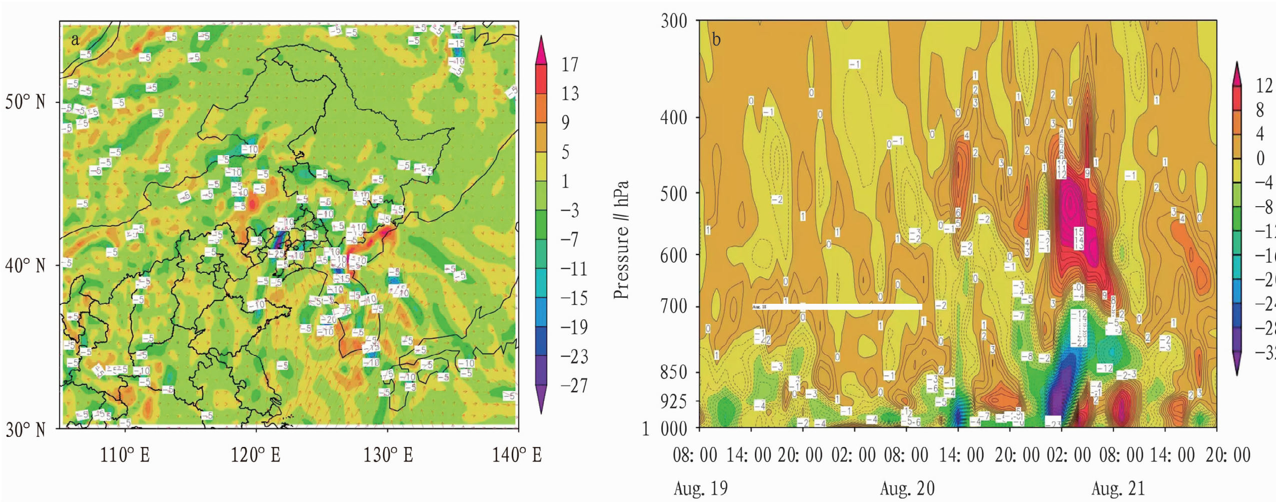


Fig. 1 Water vapor flux (arrow, unit: g/(s · hPa · cm)) and water vapor flux divergence (colored area, unit: 10^{-6} g/(s · hPa · cm)) at 850 hPa at 02:00 on August 22, 2024 (a) as well as the time – height vertical profile diagram of water vapor flux divergence (colored area, unit: 10^{-6} g/(s · hPa · cm)) at Fuxin station from 08:00 on August 19 to 20:00 on August 21, 2024

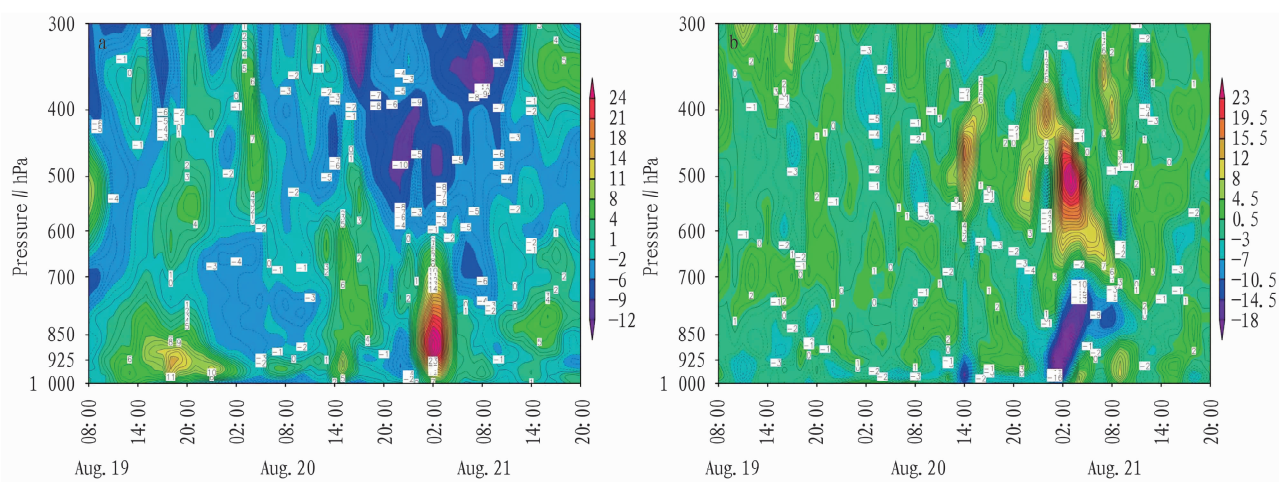
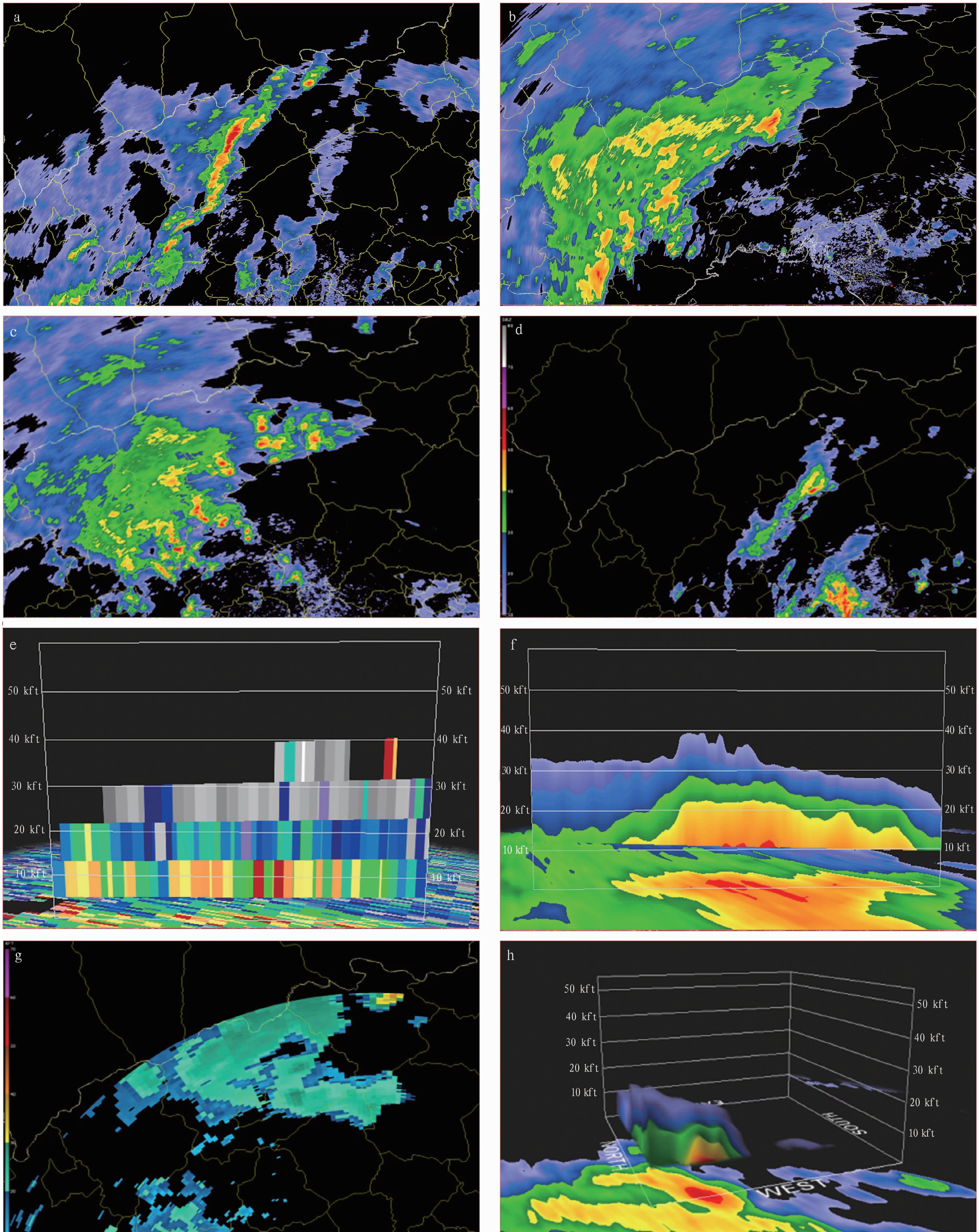


Fig. 2 Time – height vertical profile diagram of vorticity (a) and divergence (b) (colored area, unit: 10^{-4} g/(s · hPa · cm)) at Fuxin station from 08:00 on August 19 to 20:00 on August 21, 2024

tivity factor was 56 dBZ; the strong reflectivity factor of above 50 dBz extended to over 6 km, and the ZDR column of above 1 db extended to 6.9 km (Fig. 3e). The intense upward movement led to the rapid development of the convective storm, which was conducive to the occurrence of heavy precipitation. The hourly rainfall intensity in Qinghemen District of Fuxin reached 54. 8 mm/h. From 12:00 to 13:00, strong convective cells moved northeastward, and the backward propagation feature process was obvious. At 13:13 (Fig. 3a), a linear convective storm with multiple cells formed in the central part of Fuxin, so that short-term heavy precipitation with a rainfall intensity exceeding 20 mm/h appeared in several towns in the central part of Fuxin. At 04:00 on August 20, with the development of the low vortex, the southerly airflow on the east side strengthened, and the convective system continued to develop. There were large-scale layered mixed precipitation echoes in western Liaoning, and they gradually moved northward under the guidance of high-altitude airflow. From 05:00 to 09:00, the strong echoes began to affect the west of Fuxin, and at 06:22 (Fig. 3b), the maximum reflectivity factor of the convective belt in the west of Fuxin was 55 dBZ, and the strong echoes above 50 dBZ were concentrated below 0 ℃ (Fig. 3f), presenting a warm cloud feature with a low center. The precipitation efficiency was high, and rainstorms happened in 4 towns in the west of Fuxin, with the maximum hourly rainfall intensity of 57. 3 mm/h. At 14:00 on August 20, Yixian and Beizhen in the south of Fuxin were located in the convergence zone at the top of the ground trough; a β mesoscale convective complex formed, and moved northward along the high-altitude guiding airflow. During the movement, new convective cells were constantly incorporated from the east side, and affected the south of Fuxin since 15:10. From 15:00 to 22:00 (Fig. 3c), new convective cells continuously merged in Fuxin, and a large-scale rainstorm appeared in Fuxin. At



Note: a. 13:13 on Aug. 19; b. 06:22 on Aug. 20; c. 16:10 on Aug. 20; d. 13:11 on Aug. 21; e. 12:14 on Aug. 19; f. 06:22 on Aug. 20; g. 18:19 on Aug. 20; h. 13:11 on Aug. 21.

Fig. 3 Reflectivity factor at an elevation of 0.5° in Yingkou (a, b, c, d, unit: dBZ), ZDR profile map of Qinghemen District, Fuxin (e, unit: dB), vertical reflectivity factor profile (f) along the red line in Fig. 3b, echo top height (g, unit: kft), and three-dimensional reflectivity factor profile of the heavy precipitation center (h, unit: dBZ)

18:19, the convective cells strengthened in the north of Zhangwu County, and the maximum reflectivity factor was 55 dBZ (Fig. 3g); the strong reflectivity factor above 50 dBZ extended to 6.7 km, and the echo top height was 12.3 km. The convective storm developed vigorously, with a backward propagation feature, and the precipitation efficiency was high. From 18:00 to 20:00, the precipitation at Qingquan Reservoir station in Zhangwu County was 95.9 mm, and the maximum rainfall intensity was 65.5 mm/h. After 22:00, precipitation echoes began to weaken and gradually moved out of Fuxin. At 08:00 on August 21, Fuxin was located in the front of the upper-level trough, with obvious shear in the middle and lower troposphere. With ground warming in the afternoon, new convective cells emerged in the south of Fuxin from 11:00 to 13:00 on August 21, and a northeast – southwest linear convective belt formed (Fig. 3d), with obvious backward propagation characteristics. The three-dimensional profile (Fig. 3h) shows that the echo center was low, and the precipitation efficiency was high. From 13:00 to 17:00, heavy precipitation occurred in the south of Fuxin.

4.2 Analysis of satellite data From the evolution of the FY-4A infrared cloud image (omitted) at 00:00 on August 20, it can be seen that there were several relatively complete elliptical mesoscale convective cloud clusters in the southwest of Fuxin. During this period, black body temperature (TBB) was relatively low. The TBB over Fuxin ranged from –25 to –40 K. The minimum appeared in Suizhong, only –56 K. At 01:00, due to the mutual penetration of convective areas of different cloud clusters, the convective cloud clusters in the southwest of Liaoning rapidly strengthened and merged into a mesoscale convective complex. During the merging process, new convective cloud clusters were constantly triggered, resulting in a significant increase in the area of the cloud clusters, smoother edges, tighter structure, and a significant increase in cloud top height, and a decrease in TBB. At 05:00, the TBB over Fuxin dropped to –30 – –55 K, and the minimum occurred in the west of Fuxin. From 00:00 to 05:00, the cloud top height rose from 12 to 16 km, indicating that the vertical development of the convective cloud clusters in the west of Fuxin was vigorous.

These cloud clusters continuously moved and developed northward under the guidance of the shear line. Warm and humid air converged and rose near the shear line. At the same time, the interaction with the cold air penetrating from the upper atmosphere promoted the continuous development of rainstorm cloud clusters, enhancing the convective instability of the atmosphere. However, the main part of the cloud clusters moved slowly, and the center remained in the southwest of Liaoning, which was the main reason for the occurrence of extreme rainstorms in Jianchang and Suizhong. Fuxin was mainly affected by the cloud system at the top of the cloud clusters, so that a rainstorm appeared in the west of Fuxin from 05:00 to 09:00 on August 20.

5 Characteristics of microwave radiometer

As shown in the water vapor profile – height vertical section diagram (Fig. 4a) and the diagram of the relationship between water vapor and precipitation (Fig. 4b) derived from the microwave radiometer inversion at Fuxin station (54237), the atmospheric water vapor was mainly concentrated below 5 000 m. With the increase of atmospheric water vapor, short-term heavy precipitation occurred at Fuxin station at 13:00 and 14:00 on August 19, and hourly precipitation was 21.7 and 14.4 mm, respectively. Total water vapor content and liquid water path (LWP) increased significantly. The average of total water vapor content was 168.3 mm, and the maximum was up to 239.2 mm. The average of LWP was 38.8 mm, and the maximum reached 50 mm. From 15:00 on August 19 to 01:00 on August 20, there was a precipitation break, and total water vapor content ranged from 64 to 76 mm, while LWP varied from 3.7 to 6.5 mm. From 02:00 to 06:00 on August 20, precipitation occurred again, and hourly precipitation was from 0.4 to 2.8 mm. The hourly average of total water vapor content was between 76 and 85 mm, and the maximum was 119.5 mm. The hourly average of LWP was between 16.3 and 41.8 mm. From 15:00 on August 20 to 01:00 on August 21, precipitation happened two times, and the hourly aver-

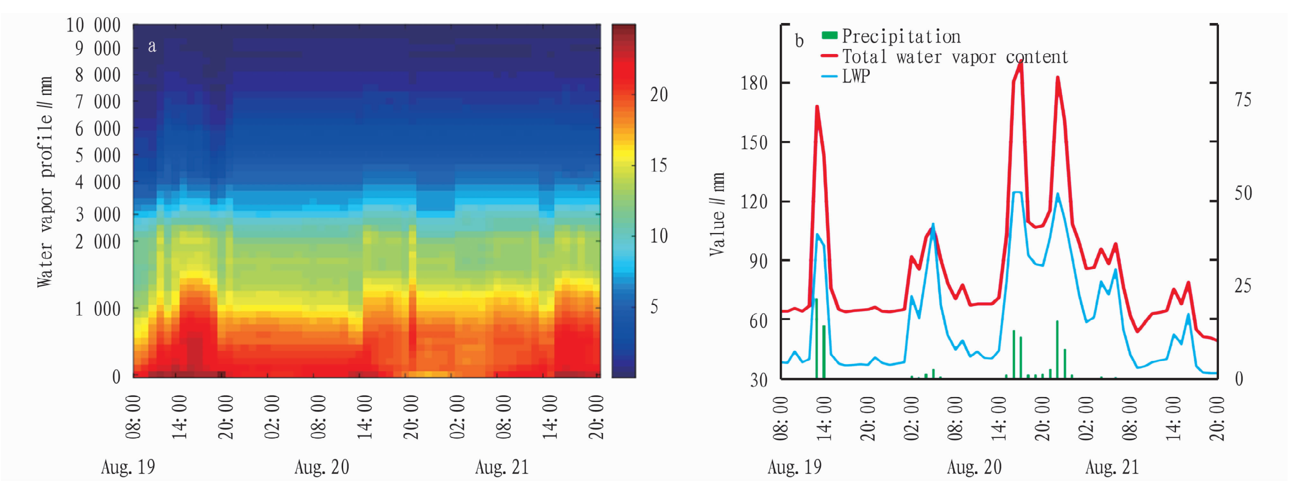


Fig. 4 Water vapor profile – height vertical section diagram (a) and the diagram of the relationship between water vapor and precipitation (b) from 08:00 on August 19 to 20:00 on August 21 in 2024

age of total water vapor content was above 105 mm, and that of LWP was above 26 mm. At 16:00, 17:00, 22:00, and 23:00, the rainfall was heavy, and the maximum of total water vapor content and LWP was up to 236.9 and 50 mm, respectively. From 04:00 to 06:00 and from 15:00 to 17:00 on August 21, hourly rainfall intensity was less than 1 mm, and the hourly average of total water vapor content was between 55 and 76 mm, while the hourly average of LWP ranged from 3.5 to 17.5 mm. As the precipitation ended at 18:00, total water vapor content dropped to 51.4 mm, and LWP reduced to 1.61 mm.

6 Conclusions

(1) This precipitation process occurred under the circulation pattern of a high-pressure system in the east and a low-pressure system in the west at 500 hPa. The subtropical high was northward and stable. The low vortex moved eastward and northward along the edge of the subtropical high. The blocking high and the cut-off low vortex system near the Ural Mountains were deep. In the rear of the cut-off low vortex, cold air continuously spread eastward and southward, and a short-wave trough formed in the middle latitudes. Cold air moved eastward to continuously converge with warm and humid air currents from the northwest side of the subtropical high over Fuxin, which was the main circulation pattern for the occurrence of this heavy precipitation event.

(2) The low-level jet stream guided the moisture from the periphery of the subtropical high to be transported to Liaoning. The southerly jet stream provided abundant moisture and energy for the rainstorm, and a water vapor convergence center formed in Fuxin. Fuxin was located in the superimposed area of the strong divergence zone on the right side of the entrance area of the high-altitude westerly jet stream and the strong convergence zone on the left front of the outlet of the low-altitude jet stream, and the upward movement was intense, which was conducive to the occurrence of heavy precipitation.

(3) As the system continued to develop, the low-level water vapor convergence center gradually extended to the upper and middle levels, indicating that the continuous water vapor supply and the strong water vapor convergence provided the necessary water vapor conditions for the rainstorm. The strengthening and maintenance of positive vorticity in the middle and lower levels were the result of the coupling effect between the low vortex and the low-level jet stream. During the period of heavy precipitation, Fuxin was located in the upper-level divergence zone and the lower-level convergence zone, and the updraft movement was strong, which was very conducive to the occurrence and maintenance of heavy precipitation.

(4) During the precipitation process from August 19 to 21, the mesoscale and small-scale convective systems all had the characteristic of backward propagation. In the early stage of the convection, the updraft movement was strong. On the infrared cloud image, TBB decreased significantly, and the cloud top height rose obviously. As the convective system developed, the newly formed convective cells merged with the mature cells, so that rainstorm cloud clusters continuously developed. The strong echo center was low, and the precipitation efficiency was high. Under the effect of the train effect, a continuous rainstorm process occurred in Fuxin.

(5) With the increase of atmospheric water vapor and liquid water content, short-term heavy precipitation appeared. At the same time, the changing trend of water vapor derived by microwave radiometer inversion was relatively consistent with that of precipitation. The continuous transportation of water vapor was a necessary condition for the occurrence of the rainstorm.

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