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Diagnostic Analysis of a Heavy Rainfall Process in Hulunbuir City

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Abstract Based on high-altitude and ground observation data and physical quantity field data, the diagnostic analysis of a heavy rainfall process in Hulunbuir City from July 18 to 20, 2025 was conducted from the aspects of circulation patterns, influencing systems, dynamic conditions, moisture conditions and convective conditions, and the causes of the occurrence and development of this process were revealed. The study shows that the superposition of the upper-level trough, the ground cyclone, and the low-level jet stream formed strong water vapor transport, strong warm advection, and strong dynamic uplift in Hulunbuir, thereby leading to this heavy rainfall event. The forecasting ideas for short-term heavy rainfall were pointed out to provide certain scientific references for future forecasting and prediction work.

Key words Heavy rainfall; Influencing system; Circulation situation; Physical quantity field

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Heavy rainfall and the resulting floods are the most frequent and severe natural disasters worldwide, and they have always been a core topic in meteorological research. Studies both at home and abroad have shown that heavy rainfall processes in middle and high latitudes are usually closely related to specific large-scale circulation patterns, and especially the classic model of "high-altitude trough (vortex) combined with ground cyclone" is the key mechanism triggering regional rainstorms. During the northward advancement of the East Asian summer monsoon system, the carried abundant water vapor and the cold air in the westerly belt converged in the northeastern region, often leading to extreme precipitation events.

Hulunbuir City is an important ecological barrier and pastoral base in northern China, and its weather system is complex and variable due to its unique geographical location. In-depth analysis of the heavy rainfall weather situation in this region is not only a practical application of weather theory but also has urgent practical significance. On the one hand, the underlying surface conditions in the Hulunbuir region are special, and heavy rainfall is prone to cause mountain floods, internal floods, and geological disasters in grasslands and forest areas, posing a serious threat to people's lives and property safety, as well as livestock production and fragile high-latitude ecosystems. On the other hand, in recent years, under the background of global climate change, extreme precipitation events have been increasing, so clarifying the circulation characteristics of localized disaster-causing rainstorms is crucial for enhancing regional disaster prevention and mitigation capability and ensuring the sustainable development of society and economy.

In this paper, based on the daily data of 500 hPa potential height field and sea level pressure field, a heavy rainfall process affecting Hulunbuir City from July 18 to 20, 2025 was studied, and the dynamic evolution of the high-altitude trough and ridge system and the ground pressure system was systematically analyzed to reveal the circulation configuration characteristics and formation mechanism of this process, so as to provide scientific references for deepening the understanding of local rainstorm weather patterns and improving the accuracy of forecasting and warning.

1 Weather conditions

From July 18 to 20, 2025, due to the influence of the northeast cold vortex, heavy rainfall occurred in Hulunbuir City. The rainfall was recorded at 388 monitoring stations across the city. This precipitation process was characterized by long duration, large and strong rainfall, and extensive coverage. The rainfall was particularly heavy in the northern and eastern regions. The cumulative rainfall at 6 monitoring stations in Moqi and 1 monitoring station in Genhe exceeded 100 mm. The maximum rainfall occurred in Kunmi'erti in Moqi, up to 131. 5 mm. The maximum hourly rainfall intensity was recorded during 15:00 – 16:00 on July 19 at this station, reaching 33. 2 mm/h. This rainfall process began successively from the night of July 18, and appeared at all 388 monitoring stations in Hulunbuir City from 20:00 on July 18 to 07:00 on July 20. Among them, the rainfall was 100 – 249. 9 m at 7 stations, 50 – 99. 9 m at 63 stations, 25 – 49. 9 m at 131 stations, 10 – 24. 9 m at 136 stations, and 0. 1 – 9. 9 m at 51 stations. The hourly rainfall intensity at 15 meteorological monitoring stations within Moqi, Zhalantun City, Yakeshi City, Genhe City, and Elunchun Autonomous Banner ranged from 20. 1 to 33. 2 m.

2 Analysis of circulation patterns

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2.1 Circulation pattern at 500 hPa The 500 hPa isobaric surface map depicts the circulation conditions of the middle and upper atmosphere, on which the trough and ridge systems are the key factors guiding the development of weather systems. At 20:00 on July 18, there was a high-altitude trough in the area from the Baikal Lake to Mongolia. At this time, the development of the weather system was in the initial stage. The northwest airflow behind the trough guided the cold air to move southward, while the southwest airflow in front of the trough was conducive to the northward transport of warm and humid air. Hulunbuir City was exactly located in front of this high-altitude trough, and the convergence and upward movement area in front of the trough was the key mechanism triggering heavy precipitation. The southwest warm and humid air converged in this area, providing abundant water vapor conditions for heavy rainfall. As the high-altitude trough moved eastward and deepened, the low trough moved to Hulunbuir City, and closed into a low vortex at 20:00 on July 19. The central intensity was 568 dagpm, and the rainfall process in Hulunbuir City peaked. At 20:00 on July 20, the low vortex continued to move eastward and deepen, continuing to affect Hulunbuir area. The isobaric height lines were still relatively dense in the west of Hulunbuir, and the central intensity increased to 564 dagpm, and the meridional extent also expanded accordingly. Intense upward movement and water vapor transport were maintained, thus causing the heavy rainfall process to continue. At 20:00 on July 21, the low vortex moved eastward, and Hulunbuir City was under the control of the northwest airflow behind the trough. The heavy rainfall process tended to come to an end.

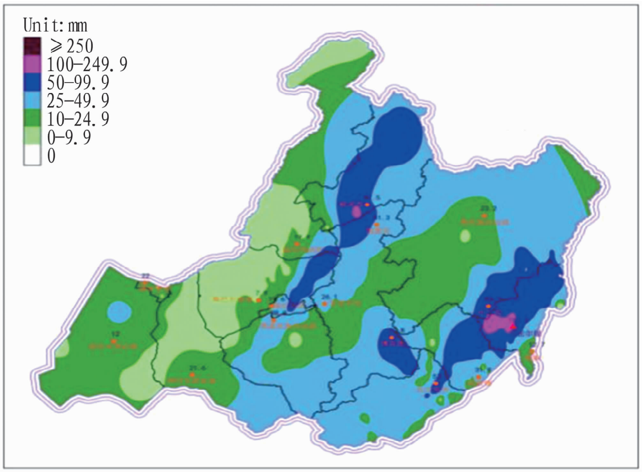

Fig. 1 Daily precipitation from June 15 to 18 in 2017

2.2 Sea level pressure field In the sea level pressure field, a ground cyclone developed in the northeastern region at 20:00 on July 19, and there existed a 1 000 hPa low-pressure center. The ground low-pressure system combined with the upper-level trough formed a typical precipitation weather system model composed of "upper trough and ground cyclone". The ground cyclone, which was the center of low-level convergence, can effectively lift the air and trigger convection. Hulunbuir City is located on the top of this ground cyclone. At 20:00 on July 20, this ground low-pressure system increased and moved northward, and the central value deepened to 990 hPa. At this time, Hulunbuir City was located behind the low-pressure system, and its center was closer to the eastern part of Hulunbuir City, while the southerly or southeastern wind to its east would transport warmer and moister air to Hulunbuir.

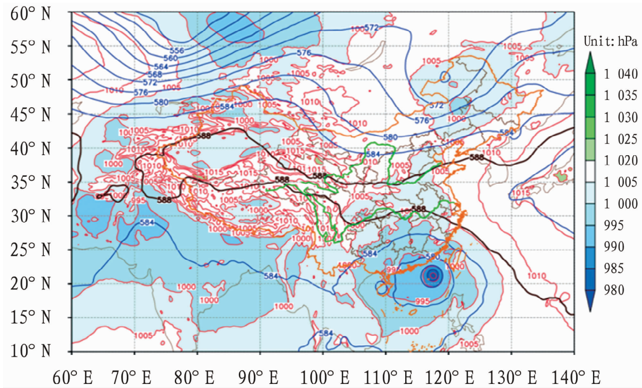

Fig. 2 Height field and sea level pressure field at 500 hPa at 20:00 on July 19, 2025

3 Analysis of causes of heavy rainfall

3.1 Analysis of abundant water vapor conditions Water vapor is the "raw material" for heavy rainfall, and its transport and concentration are mainly diagnosed through the specific humidity field and wind field at 850 hPa.

3.1.1 Abnormally abundant water vapor. From the specific humidity field at 850 hPa at 20:00 on July 19, it is seen that a high specific humidity tongue extended from the southern part of China northward, and its axis pointed towards the northern and northeastern regions of China. In the southern part of Hulunbuir, specific humidity reached around 10 – 12 g/kg. For Hulunbuir in the mid-high latitudes, the specific humidity at 850 hPa was more than 10 g/kg, which is a key threshold for the occurrence of heavy rainfall. This indicates that there was abnormally abundant water vapor in the middle- and low-level atmospheric column, and the content far exceeded the average level of this region in summer, which provided an adequate material basis for the rainstorm.

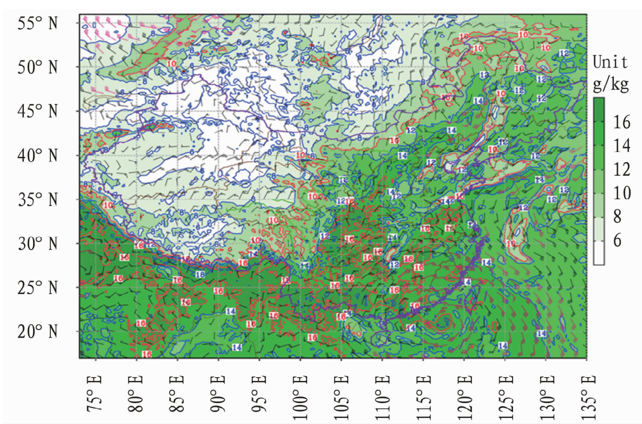

Fig. 3 Specific humidity field at 850 hPa at 20:00 on July 19, 2025

3.1.2 Continuous water vapor transport channel. From the wind field map, it can be clearly seen that in the upstream area of Hulunbuir (north of the Hexi Corridor), there existed a strong southwesterly – southerly low-level jet stream, which acted as a "water vapor conveyor belt". It continuously transported the core water vapor from the warm and humid air masses in the South China Sea and the East China Sea to the north, and converged with the ascending motion area in front of the upper-level trough in Hulunbuir. This continuous transportation ensured that precipitation cloud systems could continuously form and maintain.

3.2 Analysis of strong dynamic lifting conditions Dynamic conditions provided a "trigger mechanism" for the condensation of water vapor and precipitation.

3.2.1 Configuration of low-level convergence and high-level divergence. At 20:00 on July 19, the wind field at 850 hPa show that the strong southwest jet stream, upon reaching Hulunbuir, was affected by topographical and other factors, resulting in a significant cyclonic curvature in wind speed (wind direction rotated counterclockwise), indicating the presence of low-level convergence in this area. This convergence forced the air to rise, and in combination with the typical divergence zone before the high-level trough at 500 hPa, a coupling effect was formed. That is, the configuration of "low-level convergence and high-level divergence" constituted an extremely efficient suction pump, and generated deep and intense systematic upward movement, which is the most core dynamic mechanism for triggering and maintaining heavy rainfall.

3.2.2 Significant convergence of cold and warm air. From the 48-hour temperature change map at 850 hPa at 20:00 on July 19, a strong warm advection band can be clearly observed. In Hulunbuir and its southwest, temperature increased obviously by 8 – 12 ℃. The strong warm advection had a dual effect. One is the dynamic uplifting effect, and the advection itself corresponded to large-scale ascending motion. The other is the thermal effect, and provided heat for the increase of atmospheric stability instability. It is an important source of convective instability energy to be analyzed below.

3.3 Analysis of favorable convection instability conditions Heavy rainfall, especially short-term heavy precipitation, is often accompanied by convective activities, which is closely related to the instability of the atmosphere.

3.3.1 Unstable environment with high energy and humidity. K index is an important indicator for measuring the stability of the atmospheric stratification and the degree of warmth and humidity. Generally, when K index is greater than 35 ℃, the atmosphere is in an unstable state, which is conducive to the development of convection. From the K index field at 20:00 on July 19, a high-value area (35 – 40 ℃) expanded northward from North China, and its front exactly covered or approached Hulunbuir. This indicates that the atmosphere above Hulunbuir became warm, humid, and unstable, and contained a large amount of potential convection energy. Once there was sufficient lifting triggering mechanism (such as the dynamic lifting analyzed earlier), the energy would be released and transformed into vigorous convection cloud clusters, generating thunderstorms and short-term heavy precipitation.

3.3.2 Triggering of unstable energy. The aforementioned low-level convergence line, the positive vorticity advection before the upper-level trough, and terrain uplift jointly played the role of "pulling the trigger", and triggered the unstable energy in this region.

4 Conclusions

(1) This precipitation process had the characteristics of long duration, large and strong rainfall, and extensive coverage.

(2) From July 20 to 21, 2025, under the combined effect of a deep upper-level trough developing from Baikal Lake to Mongolia and the lower Mongolian cyclone, Hulunbuir City experienced this intense rainfall process. The upper-level trough provided the driving uplift and water vapor transport, while the ground cyclone strengthened the low-level convergence. The perfect coordination of these two factors was the fundamental cause of this heavy rainfall weather.

(3) Water vapor supply: a strong low-level southwest jet stream, as the "water vapor conveyor belt", transported exceptionally abundant water vapor. Physical trigger: the low-level convergence at 850 hPa provided a trigger point for the near-ground layer uplift, and the upper-level trough at 500 hPa provided a suction and guiding mechanism for the upper layer. Unstable energy: intense low-level warm advection and abundant water vapor jointly constructed an unstable environment with high K index. This circulation configuration and physical quantity characteristics are the key signals for forecasting such heavy rainfall weather.

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