Evolution Characteristics of a Mesoscale Convective System During a Convective Heavy Rainfall Event in the Hetao Region, Inner Mongolia (Postprint)

Authors: Huang Xiaolu

Date: 2023-01-17T00:00:00+00:00

Abstract

Using conventional observational data, FY4A satellite, Doppler weather radar, and reanalysis data, an analysis was conducted on the circulation background, environmental conditions, and evolution characteristics of mesoscale convective systems (MCSs) during the heavy rainstorm event in the Hetao region of Inner Mongolia on July 19, 2018. The results indicate that: (1) The stable and quasi-stationary subtropical high, 500 hPa upper-level trough, low-level shear line and southwest jet, 300 hPa upper-level jet, and surface low pressure system collectively provided a favorable circulation background for this convective rainstorm event. (2) The persistent low-level southwest jet provided abundant water vapor transport, while the high-energy tongue of pseudo-equivalent potential temperature, deep warm cloud layer, high convective available potential energy, cold advection intrusion behind the upper-level trough, and the unstable stratification with dry air aloft and moist air below provided favorable environmental conditions for the development of severe convective rainstorms. (3) MCSs that developed in both east-west and north-south orientations jointly contributed to the heavy rainstorm event. The convective rainstorm was primarily generated by the east-west oriented MCS moving slowly along the Yinshan Mountains. Heavy precipitation exceeding 20 $\mathrm{mm \cdot h^{-1}}$ occurred near the edge of the upwind cloud cluster and in regions with large gradients of cloud top brightness temperature (TBB). (4) The east-west oriented band echo moved slowly with its propagation direction essentially parallel to its long axis. The slow eastward movement of strong echoes formed a significant "train effect," producing continuous heavy precipitation for over 5 hours. The north-south oriented band echo persisted longer, but its movement direction was perpendicular to its long axis and its speed was faster, resulting in weaker rainstorm intensity compared to the east-west oriented system. (5) The surface mesoscale convergence line was the primary triggering mechanism for the mesoscale convective systems. The complex terrain of the Hetao region and pulsations in the low-level jet further promoted convective initiation. The surface mesoscale convergence line exhibited a distribution that nearly overlapped with the Yinshan Mountains, which favored the persistence of precipitation and contributed to the occurrence of this convective rainstorm event.

Full Text

Abstract

Based on conventional observation data, FY-4A satellite imagery, Doppler weather radar data, and reanalysis datasets, this study analyzes the synoptic background, environmental conditions, and evolution characteristics of the mesoscale convective system (MCS) associated with a heavy rainfall event in the Hetao region of Inner Mongolia on July 19, 2018. The results indicate: (1) The stable maintenance of the western Pacific subtropical high, in conjunction with a 500 hPa upper-level trough, low-level shear line and southwest jet, 300 hPa upper-level jet stream, and surface low pressure system, provided a favorable large-scale circulation background for this convective heavy rainfall process. (2) The persistent low-level southwest jet supplied abundant moisture transport. A high-energy tongue of pseudo-equivalent potential temperature, a deep warm cloud layer, high-intensity convective available potential energy (CAPE), cold advection intrusion behind the upper-level trough, and an unstable atmospheric layer with dry air aloft and moist air below created favorable environmental conditions for severe convective rainfall. (3) Two MCSs, oriented east-west and north-south respectively, developed sequentially and jointly produced the heavy rainfall event. The convective rainfall in the main heavy rainfall area was primarily generated by the east-west oriented MCS moving slowly along the Yinshan Mountains, producing a “train effect.” Short-duration heavy rainfall exceeding 20 $\mathrm{mm \cdot h^{-1}}$ occurred near the edge of upwind cloud clusters and in regions with large gradients of cloud top brightness temperature (TBB). (4) During the severe convective rainfall stage, the east-west oriented banded echo exhibited a large spatial extent, large scale, and strong intensity, with characteristics of low-center warm-cloud precipitation. Its slow movement speed and movement direction essentially parallel to the long axis of the echo band created a significant “train effect,” resulting in continuous heavy rainfall exceeding 50 mm for over five hours. Although the north-south oriented banded echo persisted longer than the east-west echo, its movement direction was perpendicular to the long axis of the echo band and its movement speed was relatively faster, resulting in weaker rainfall intensity compared to the east-west oriented system. (5) The surface mesoscale convergence line was the primary triggering mechanism for the MCS. The complex terrain of the Hetao region and pulsations in the low-level jet further promoted convective initiation. The surface mesoscale convergence line exhibited a distribution pattern that almost overlapped with the Yinshan Mountains, which was conducive to sustaining precipitation and facilitating the occurrence of this convective heavy rainfall event.

Keywords: convective heavy rainfall; mesoscale convective system; train effect; Hetao region; Inner Mongolia

Introduction

Heavy rainfall represents the primary disastrous weather phenomenon during summer in Inner Mongolia. In recent years, accompanying global climate warming, extreme heavy rainfall events have occurred frequently, showing a more pronounced increasing trend in the Hetao region of Inner Mongolia [Figure 1: see original paper]. The Hetao region features complex terrain with alternating distribution of deserts, mountains, and oases, situated in an arid and semi-arid zone with extremely fragile ecological environments. Rainfall events in this region are characterized by concentrated scope and strong suddenness, easily triggering secondary disasters such as landslides, debris flows, and flash floods, which not only affect local production and life but also cause casualties and severe economic losses. Convective heavy rainfall events, which account for most heavy rainfall occurrences, are products of multi-scale system interactions [Figure 2: see original paper].

Many scholars have conducted in-depth research on heavy rainfall processes in arid and semi-arid zones from perspectives of circulation background, moisture conditions, and physical quantity evolution [Figure 3: see original paper]. In recent years, with the application of multi-source high-resolution data from radar, satellite, and automatic weather stations, research on the characteristics of convective heavy rainfall and associated mesoscale influencing systems has become increasingly comprehensive [Figure 4: see original paper]. Convective heavy rainfall is typically triggered by mesoscale and small-scale systems under favorable circulation backgrounds [Figure 5: see original paper]. Under suitable environmental conditions, the combined effects of low-level wind shear, low-level jet speed pulsations, boundary layer convergence lines, and terrain serve as the primary reasons for triggering mesoscale convective system (MCS) development and intensification [Figure 6: see original paper]. Favorable dynamic and thermal factors play important roles in MCS initiation and propagation [Figure 7: see original paper], while terrain also significantly influences MCS development. Complex terrain facilitates the formation of low-level convergence centers, and mountain blocking promotes dynamic lifting and back-building of convective cells, thereby affecting MCS maintenance and development [Figure 8: see original paper].

Previous research on heavy rainfall causes in the Hetao region of Inner Mongolia [Figure 9: see original paper] has lacked in-depth analysis of mesoscale system evolution characteristics and formation mechanisms of convective heavy rainfall in this area. On July 19, 2018, a heavy rainfall event occurred in the Hetao region of Inner Mongolia, with intense precipitation mainly along the southern foothills of the Yinshan Mountains, causing urban waterlogging, communication disruptions, flash floods, 5 deaths, and severe losses. This paper analyzes the evolution characteristics and triggering mechanisms of the MCS in this event, aiming to provide theoretical basis and guidance for improving convective heavy rainfall forecasting in this region.

1. Data Selection

The observation data used in this study include surface observations from conventional meteorological stations, densely distributed automatic weather stations, FY-4A infrared satellite imagery, and Doppler weather radar data from Ordos, Inner Mongolia, covering the period 02:00–16:00 BT on July 19, 2018. Reanalysis datasets include NCEP/NCAR data (spatial resolution 1°\$×1°,*temporalresolution6h)andECMWFdata(spatialresolution0.25°×0.25°,temporalresolution6h)fromt*
RangeWeatherForecasts.TopographicdatawereobtainedfromtheNationalFundamentalGeographicInforma
km).

2. Precipitation Overview and Characteristics

The heavy rainfall event on July 19, 2018, exhibited distinct features of convective heavy rainfall. Figure 1 shows the accumulated precipitation from 06:00 to 18:00 BT and hourly precipitation distribution. The precipitation covered a wide area, with the heavy rainfall zone exhibiting a banded distribution oriented east-west. Heavy rain and downpour areas were mainly located along the southern foothills of the Yinshan Mountains, with 28 stations recording precipitation exceeding 100 mm, and the maximum precipitation reaching 174.5 mm at Yangliuqibu in Baotou. Precipitation primarily occurred between 06:00 and 15:00 BT, with 11 stations experiencing multiple occurrences of short-duration heavy rainfall ($>$20 $\mathrm{mm \cdot h^{-1}}$). Notably, Yangliuqibu station recorded extreme short-duration heavy rainfall of 84.7 mm between 07:00 and 08:00 BT. The event was also accompanied by thunderstorm and gusty wind activity. Figure 1c shows the hourly lightning frequency variation from 04:00 to 14:00 BT, indicating thunderstorm activity lasting over 10 hours, with the most frequent period occurring between 06:00 and 10:00 BT, peaking at 116 lightning strikes in Baotou's Baiyun Obo. In summary, this precipitation event was characterized by high intensity, concentrated heavy rainfall area, and close association with thunderstorms, short-duration heavy rainfall, and terrain.

3. Circulation Background and Environmental Conditions

3.1 Circulation Characteristics

The heavy rainfall event in the Hetao region occurred on the periphery of the western Pacific subtropical high. At 08:00 BT on July 19, the 500 hPa geopotential height field (Figure 2) shows that the western Pacific subtropical high exhibited a zonal pattern located in the middle and lower reaches of the Yangtze

River. Influenced by a typhoon in the tropical region, the 588 dagpm contour of the subtropical high extended westward to the south of the Hetao region and remained stable throughout the event, facilitating continuous transport of warm and moist air from tropical and subtropical regions into the Hetao area along the subtropical high. An upper-level trough moved eastward upstream of the Hetao region, with dry and cold air behind the trough converging with warm and moist air, favoring severe convective weather development. At 700 hPa, under the combined influence of a southwest low-level jet and a "human-shaped" shear line, the Hetao region was located on the left front side of the low-level jet and south of the warm shear line, with strong convergence and upward motion providing favorable dynamic conditions. The heavy rainfall area occurred near the surface low-pressure center (figure omitted), with surface temperatures at 02:00 BT reaching 25°C, indicating that the lower atmosphere was warm and moist with potential for severe convective weather. The stable maintenance of the subtropical high, the 500 hPa upper-level trough, 700 hPa shear line and southwest low-level jet, 300 hPa upper-level jet, and surface low pressure provided favorable large-scale circulation background for this heavy rainfall event. However, heavy or torrential rainfall also requires coordination of sufficient moisture conditions, stratification conditions, and lifting mechanisms, which are analyzed below.

3.2.1 Water Vapor Conditions

Figure 3 shows the 700 hPa water vapor flux and specific humidity distribution at 08:00 BT on July 19. A distinct moisture transport belt extended to the Hetao region, corresponding to the southwest warm and moist jet. The formation and maintenance of the low-level jet were closely related to this heavy rainfall event. The low-level jet intensity continuously strengthened, reaching its maximum at 08:00 BT with a central wind speed of 18 $\mathrm{m \cdot s^{-1}}$. The stable and quasi-stationary low-level jet persisted over the heavy rainfall area for more than 10 hours. The heavy rainfall zone was located on the left front side of the low-level jet exit region, which favored the generation of cyclonic shear and continuously brought warm and moist airflow to the lower levels. A high-value tongue of water vapor flux greater than 20$×10^{-6}$ $\mathrm{g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}}$ penetrated into the Hetao region, promoting moisture transport and enhancing atmospheric stratification instability. The specific humidity in the heavy rainfall area exceeded 10 $\mathrm{g \cdot kg^{-1}}$ at 700 hPa, showing a distinct moist tongue with a maximum value of 12 $\mathrm{g \cdot kg^{-1}}$.

A vertical cross-section along 40°N through the heavy rainfall area (Figure 3b) reveals that the high-value zone of water vapor flux coincided with the convergence area of water vapor flux divergence. Significant southwest jets existed in the middle and lower layers, facilitating vertical moisture transport. A water vapor flux divergence convergence zone was evident from the surface to 500 hPa, with divergence above 500 hPa, further promoting moisture accumulation and indicating deep vertical moisture accumulation. The specific humidity in the heavy rainfall area remained stable between 6–15 $g \cdot kg^{-1}$ from 850–500 hPa. The water vapor transport for this heavy rainfall event primarily originated from the southwest wind jet in the middle and lower layers, which not only promoted dynamic convergence and lifting at low levels but also, through its stable maintenance, facilitated continuous transport of warm and moist air from the south, promoting moisture convergence and accumulation in the heavy rainfall area. The extreme short-duration heavy rainfall of 90 mm at Yangliuqibu station between 07:00–08:00 BT was closely related to the significant humidity increase under the action of the low-level jet.

3.2.2 Layer Stability

Pseudo-equivalent potential temperature (_{se}) is a comprehensive characteristic quantity representing atmospheric temperature, pressure, and humidity, whose horizontal and vertical distribution can reflect atmospheric energy distribution and stratification stability [Figure 10: see original paper]. Figure 4 shows the vertical cross-section of _{se} and temperature advection along 40°N at 08:00 BT. From the surface to 500 hPa, _{se} decreased with height, exhibiting an inverted funnel-shaped distribution with increasing vertical gradient, indicating obvious convective instability stratification. The _{se} high-energy tongue extended northward to the Hetao region and beyond, favoring the accumulation of unstable energy. The K-index in the heavy rainfall area reached 35°C or higher, and convective available potential energy (CAPE) generally ranged from 300–1000 $J \cdot kg^{-1}$ (figure omitted), indicating abundant unstable energy from all aspects, favorable for convective heavy rainfall occurrence.

The temperature advection vertical cross-section shows warm advection throughout the entire layer in the heavy rainfall area, with particularly strong warm advection at low levels. The upstream area was influenced by northwesterly winds at middle and high levels, with cold advection intrusion. The intersection of cold and warm advection favored the triggering of unstable energy in the heavy rainfall area. The horizontal gradient of _{se} was more significant at low levels, indicating the existence of an energy front zone with obvious atmospheric moist baroclinicity, favorable for MCS development.

Figure 5a shows the sounding curve for Yangliuqibu station at 08:00 BT, corrected using surface temperature and dewpoint temperature. Below 750 hPa, the atmosphere was relatively moist with T-Td < 5°C, while above 750 hPa, T-Td > 15°C, indicating dry air intrusion and a significant characteristic of dry air above and moist air below, providing good thermal instability conditions. The lifting condensation level was low at 0.81 km, with a deep warm cloud layer of 5.68 km thickness. A low-level inversion layer existed, favoring the accumulation of unstable energy. CAPE reached 2801.6 $J \cdot kg^{-1}$, the K-index was 38°C, and the Lifted Index and Showalter Index were -1.9°C and -1.11°C respectively, indicating strong layer instability. The 0–6 km vertical wind shear was 19 $m \cdot s^{-1}$, with moderate vertical wind shear favorable for the development and maintenance of well-organized convective storms [Figure 11: see original paper].

3.2.3 Lifting Conditions

Figure 5b shows the time-height profile of vertical velocity at the heavy rainfall center (41°N, 109°E) from 18:00 BT on July 18 to 02:00 BT on July 20. Upward motion began at 02:00 BT, consistent with the onset of precipitation. By 08:00 BT, upward motion significantly intensified, with strong upward motion maintained throughout the entire layer from 08:00–14:00 BT. The upward motion in the middle and upper layers was particularly strong, persisting for a long duration, corresponding to short-duration heavy rainfall at multiple stations in the Hetao region. The strongest upward motion occurred at 500 hPa around 08:00–10:00 BT. After 14:00 BT, convective clouds gradually weakened and dissipated, precipitation decreased to about 10 $\mathrm{mm \cdot h^{-1}}$, and downward motion began to appear with gradually decreasing rainfall intensity. Strong lifting motion favored convective heavy rainfall occurrence, and the longer its duration, the stronger the heavy rainfall intensity.

4. Structure Characteristics, Development, and Triggering Mechanism of the Mesoscale Convective System

4.1 Structural Characteristics of the MCS in FY-4A Satellite Imagery

The mesoscale convective system (MCS) is the primary contributor to short-duration heavy rainfall in extreme precipitation events [Figure 12: see original paper]. The evolution of high spatiotemporal resolution FY-4A infrared satellite imagery (Figure 6) shows that two MCSs developed sequentially, causing the convective heavy rainfall process in the Hetao region. At 04:00 BT, a strong isolated convective cloud cluster (MCS1) formed in the northern Hetao region, with 20 $\mathrm{mm \cdot h^{-1}}$ heavy rainfall already occurring on its upwind side. By 06:00 BT, the cloud top brightness temperature (TBB) decreased to $\leq$-52°C, the cloud area gradually expanded, and the convective cloud cluster strengthened and developed into an MCS with a horizontal scale of 400–500 km. At 08:00 BT, TBB decreased to below -60°C, marking the most vigorous stage of MCS1, which moved slowly eastward along the Yinshan Mountains. Between 08:00–10:00 BT, MCS1 remained quasi-stationary along the mountainous area of the Hetao region, with its long axis direction essentially parallel to the movement direction. Heavy rainfall exceeding 20 $\mathrm{mm \cdot h^{-1}}$ appeared near the edge of upwind cloud clusters and in regions with large TBB gradients. When TBB was below -60°C, extreme short-duration heavy rainfall exceeding 80 $\mathrm{mm \cdot h^{-1}}$ occurred near the large gradient areas.

After 12:00 BT, MCS1 gradually weakened and dissipated. Meanwhile, another convective cloud cluster (MCS2) developed in the southern Hetao region, reaching a horizontal scale of 300 km by 12:00–14:00 BT. MCS2 moved and intensified with its long axis direction essentially perpendicular to its movement direction. Although heavy rainfall exceeding 20 $\mathrm{mm \cdot h^{-1}}$ also occurred near the large gradient areas, the faster movement speed prevented sustained heavy rainfall at the same location, resulting in weaker precipitation intensity compared to the first stage MCS1.

From generation to dissipation, both MCSs were accompanied by short-duration heavy rainfall of varying intensities, persisting for over 10 hours and causing the extensive heavy precipitation event. The MCSs were the direct producers of the severe precipitation, with the heavy rainfall in the main downpour area primarily generated by the "train effect" produced by the slow-moving MCS1 along the Yinshan Mountains.

4.2 Movement Characteristics of the MCS in Radar Echoes

Precipitation intensity is closely related to the movement speed, direction, and intensity of the MCS. The larger the scale of high rainfall rate areas along the movement direction and the slower the system moves, the longer the duration and the more likely severe precipitation becomes. Figure 7 shows the evolution of composite reflectivity from the Ordos Doppler radar during the heavy rainfall event, indicating that the process was mainly influenced by east-west and north-south oriented banded echoes.

Initially (figure omitted), scattered strong echoes with reflectivity >55 dBZ formed in the northwest upstream of the heavy rainfall area. Under the influence of the low-level southwest jet, new strong echoes continuously developed and moved northeastward along the low-level jet. By 05:38 BT, the precipitation echoes gradually merged and intensified. By 06:58 BT, they had merged into an east-west oriented banded strong echo (Figure 7c) with a length exceeding 300 km and reflectivity between 35–55 dBZ. A north-south oriented echo also began to form with a length of about 200 km. By 08:02 BT, both echoes further intensified, with reflectivity reaching 40–60 dBZ and precipitation intensifying, with hourly rainfall at some stations exceeding 50 $\mathrm{mm \cdot h^{-1}}$. The east-west oriented echo maintained a tight structure and moved slowly eastward along the Yinshan Mountains, with new convective cells continuously generating on its west side, exhibiting back-building propagation characteristics and causing extensive heavy rainfall exceeding 20 $\mathrm{mm \cdot h^{-1}}$, even >80 $\mathrm{mm \cdot h^{-1}}$. After 11:10 BT, the east-west banded echo weakened and broke apart during its eastward movement, while the north-south banded echo persisted longer but moved relatively faster.

Analysis of the vertical cross-section of radar reflectivity factor during the vigorous stage (Figure 7e, f) shows that the strong echo centers >50 dBZ were all below 9.56 km, characteristic of low-center warm-cloud precipitation. The east-west banded echo maintained a continuous and compact structure, with low-level strong echoes reaching >50 dBZ, indicating that this heavy rainfall process featured large-scale, intense east-west banded echoes with slow movement speed, essentially parallel to the long axis direction, forming a significant "train effect" that promoted the heavy rainfall event. Although the north-south oriented echo persisted longer than the east-west echo, its movement direction was perpendicular to the long axis and its movement speed was relatively faster, resulting in weaker rainfall intensity.

4.3 Triggering Mechanism of the MCS

Synoptic-scale upward motion typically does not directly trigger convection; upward motion that triggers convection is mostly provided by mesoscale systems [Figure 13: see original paper]. The Hetao region has complex terrain and diverse landforms, surrounded by mountains, rivers, and deserts, with the Yinshan Mountains to the north (elevation 1500–2300 m) and the Mongolian Plateau to the south (elevation 1300–1500 m), creating undulating topography. The evolution characteristics of surface wind fields were analyzed using hourly data and terrain data.

Figure 8 shows that from 04:00 BT, an east-west oriented surface mesoscale convergence line formed in the Hetao region (black dashed line), with its orientation essentially consistent with the Yinshan Mountains. On the windward slope of the Yinshan Mountains' southern foothills, surface wind speeds strengthened, with southerly winds reaching $>8\ \mathrm{m \cdot s^{-1}}$ on the south side. The convergence in the divergence field at low levels also significantly intensified, corresponding to radar echo development with gradually increasing reflectivity, reaching maximum reflectivity >50 dBZ and enhanced precipitation with hourly rainfall of 30–60 mm. The east-west oriented surface mesoscale convergence line remained stable and quasi-stationary over the heavy rainfall area from 04:00–10:00 BT, with strong convergence zones also maintained. After 10:00 BT, as the east-west mesoscale convergence line weakened and moved eastward, the convergence center gradually shifted eastward and precipitation intensity decreased to about $10\ \mathrm{mm \cdot h^{-1}}$. The north-south oriented mesoscale convergence line persisted upstream of the Hetao region from 04:00–08:00 BT, then began moving eastward, lasting until 18:00 BT and affecting the Hetao region, with precipitation intensity mainly maintained at $10–20\ \mathrm{mm \cdot h^{-1}}$.

In summary, the east-west and north-south oriented surface mesoscale convergence lines corresponded closely with the positions of radar banded echoes, indicating that the primary triggering mechanism for the MCS in this heavy rainfall event was the surface mesoscale convergence line. Its formation, maintenance, and movement promoted the initiation and development of the MCS. This heavy rainfall event was also closely connected with terrain effects. The heavy rainfall area was mainly located on the windward slope of the Yinshan Mountains' southern foothills. The prevailing southerly low-level jet entering the Hetao region was blocked by the Yinshan Mountains. On one hand, the high elevation and steep slopes of the mountains forced the southerly warm and moist jet to ascend; on the other hand, upstream cold air entering the heavy rainfall area caused strong convergence of cold and warm airflow under the action of the windward slope, further promoting upward motion and enhancing precipitation efficiency. The special terrain of the Hetao region thus provided favorable conditions for MCS triggering. This convective heavy rainfall event was closely related to surface convergence lines, terrain lifting along the Yinshan Mountains, and pulsations in the low-level jet. The surface mesoscale convergence line was the main reason for triggering the MCS, and its consistent distribution with the Yinshan Mountains favored sustained precipitation, leading to this heavy rainfall event.

5. Conclusions

Using conventional meteorological observation data, satellite cloud imagery, Doppler radar data, and reanalysis datasets, this paper conducted a detailed analysis of the circulation background, environmental conditions, evolution characteristics, and triggering factors of the convective heavy rainfall event in the Hetao region of Inner Mongolia on July 19, 2018. The main conclusions are as follows:

1. This heavy rainfall event was characterized by high intensity, long duration, concentrated heavy rainfall area, obvious convective precipitation features, and close relationship with terrain. The stable maintenance of the subtropical high, coordinated with the 500 hPa upper-level trough, low-level shear line and southwest low-level jet, 300 hPa upper-level jet, and surface low pressure system, provided favorable large-scale circulation background conditions for this convective heavy rainfall process.

2. The stable maintenance of the low-level southwest jet provided abundant moisture transport. The high-energy tongue of pseudo-equivalent potential temperature, deep warm cloud layer, "tall and narrow" high-intensity CAPE, cold advection intrusion behind the upper-level trough, and unstable atmospheric layer with dry air aloft and moist air below provided favorable environmental conditions for the generation of severe convective heavy rainfall.

3. Two MCSs, oriented east-west and north-south respectively, developed sequentially and jointly caused this heavy rainfall event, persisting for over 10 hours. The convective rainfall in the main heavy rainfall area was primarily produced by the "train effect" generated by the east-west oriented MCS moving slowly along the Yinshan Mountains. Short-duration heavy rainfall exceeding $20\ \mathrm{mm \cdot h^{-1}}$ occurred near the edge of upwind cloud clusters and in regions with large TBB gradients, with precipitation intensity closely related to the development degree of convective cloud clusters.

4. During the severe convective rainfall stage, the east-west oriented banded echo featured large spatial extent, large scale, and strong intensity, with characteristics of low-center warm-cloud precipitation. Its slow movement speed and movement direction essentially parallel to the long axis of the echo band created a significant "train effect," resulting in continuous heavy rainfall exceeding 50 mm for over five hours. Although the north-south oriented echo persisted longer than the east-west echo, its movement direction was perpendicular to the long axis and its movement speed was

relatively faster, resulting in weaker rainfall intensity.

5. The surface mesoscale convergence line was the primary triggering mechanism for the MCS. The complex terrain of the Hetao region and pulsations in the low-level jet further promoted convective initiation. The distribution pattern of the surface mesoscale convergence line that almost overlapped with the Yinshan Mountains was conducive to sustaining precipitation and facilitating the occurrence of this convective heavy rainfall event.

References

[1] Song Guiying, Li Xiaoze, Sun Yonggang, et al. Characteristics and causes of the extreme rainstorm on July 20, 2012 in the arid and semiarid zone in Inner Mongolia[J]. Journal of Glaciology and Geocryology, 2013, 35(4): 883-889.

[2] Zhang Guilian, Hang Yuehe, Fu Lijuan, et al. Causes of a torrential rainstorm induced by train effect in Hetao area[J]. Plateau Meteorology, 2020, 39(4): 788-795.

[3] Ma Aihua, Yue Dapeng, Zhao Jingbo, et al. Spatiotemporal variation and effect of extreme precipitation in Inner Mongolia in recent 60 years[J]. Arid Zone Research, 2020, 37(1): 74-85.

[4] Wang Chenghai, Yang Jintao, Yang Kai, et al. Changing precipitation characteristics in the Yellow River basin in the last 60 years and tendency prediction for next 30 years[J]. Arid Zone Research, 2022, 39(3): 708-722.

[5] Ding Yihui. Contributions of Prof Tao Shiyan to the study of formation conditions and mechanisms of heavy rainfalls in China[J]. Chinese Journal of Atmospheric Sciences, 2014, 38(4): 616-626.

[6] He Guangbi, Zeng Bo, Yu Shuhua, et al. Analysis of durative rainstorm characteristics occurred in the ambient area of Qinghai-Xizang Plateau[J]. Plateau Meteorology, 2016, 35(4): 865-874.

[7] Li Xiaoxia, Shang Dacheng, Chen Yun, et al. Mesoscale analysis on two different intensity rainstorm processes in the east of Gansu Province[J]. Plateau Meteorology, 2013, 32(5): 1389-1399.

[8] Liu Xinwei, Ye Peilong, Fu Jing, et al. The influence of the morphological evolution of plateau shear line on a precipitation weather process over plateau slope[J]. Plateau Meteorology, 2020, 39(2): 245-253.

[9] Zhao Qingyun, Zhang Wu, Chen Xiaoyan, et al. Propagation characteristics of mesoscale convection system in an event of severe convection rainstorm over both sides of Liupanshan Mountains[J]. Plateau Meteorology, 2018, 37(3): 767-776.

[10] Wang Jingsong, Li Yaohui, Kang Fengqin, et al. Characteristic quantity analyses of boundary layer from mesoscale model[J]. Plateau Meteorology, 2002,

21(3): 258-266.

[11] Yang Xiaojun, Ye Peilong, Xu Lili, et al. The variation characteristics of mesoscale convection system in a severe convective torrential rain over the northeast slope of the Qinghai-Xizang Plateau[J]. Plateau Meteorology, 2022, 41(4): 839-849.

[12] Jing Xi, Li Qiang, Tu Nini, et al. Analysis on characteristics and causation of a meso-β scale paroxysmal rainstorm on Loess Plateau[J]. Torrential Rain and Disasters, 2013, 32(3): 242-248.

[13] Zeng Yong, Yang Lianmei. Mesoscale characteristic analysis of a severe convective weather with torrential rain in the west of southern Xinjiang[J]. Journal of Arid Meteorology, 2017, 35(3): 475-484.

[14] Zhang Jiaguo, Zhou Jinlian, Chen Wei, et al. The structure and propagation characteristics of the extreme rain producing MCS on the west side of Dabie Mountain[J]. Acta Meteorologica Sinica, 2015, 41(2): 291-304.

[15] Fu Shuangxi, Zhang Hongfen, Yang Lijie, et al. Comparative analysis of different types of precipitation characteristics in the northern foot of Qilian Mountain under the influence of topography[J]. Arid Zone Research, 2021, 38(5): 1226-1234.

[16] Wang Baojian, Kong Xiangwei, Fu Chao, et al. Analysis on mesoscale characteristics of a rainstorm process in southeastern Gansu[J]. Plateau Meteorology, 2016, 35(6): 1551-1564.

[17] Fu Shuangxi, Zhang Hongfa, Chu Rongzhong. Analyzing on a heavy precipitation with doppler radar data in the middle of Hexi Corridor[J]. Arid Zone Research, 2009, 26(5): 656-663.

[18] Han Jingwei, Wu Xuehong, Song Guiying, et al. Characteristic analysis of prolonged drought turning to rain in Inner Mongolia in spring 2006[J]. Scientia Meteorologica Sinica, 2009, 29(2): 235-240.

[19] Mu Jianli, Li Zechun, Chen Yun, et al. Feature analyses of mesoscale convective system of a heavy rainfall in the central Shaanxi plain[J]. Plateau Meteorology, 2014, 33(1): 148-161.

[20] Li Chunxiao, Dong Zhibao, Xu Yongwang, et al. Cause of a local heavy rain in Ejina Banner, Inner Mongolia[J]. Journal of Desert Research, 2011, 31(3): 774-779.

[21] Yu Xiaoding. Investigation of Beijing extreme flooding event on 21 July 2012[J]. Meteorological Monthly, 2012, 38(11): 1313-1329.

[22] Meng Xuefeng, Sun Yonggang, Sa Rina, et al. Correlation between eastward developing of Hetao cyclone and the severe rainstorm in Beijing on 21 July 2012[J]. Meteorological Monthly, 2013, 39(12): 1542-1549.

[23] Sun Jisong, He Na, Wang Guorong, et al. Preliminary analysis on synoptic configuration evolvement and mechanism of a torrential rain occurring in Beijing on 21 July 2012[J]. Torrential Rain and Disasters, 2012, 31(3): 218-225.

[24] Doswell C A. The distinction between large scale and mesoscale contribution to severe convection: a case study example[J]. Weather Forecast, 1987, 2(1): 3-16.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.