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Mesoscale Characteristics and Physical Parameter Configuration of Short-duration Heavy Rainfall in Northern Gansu (Postprint)

Authors: Qian Li

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Abstract

Using precipitation data from 27 national automatic weather stations and 635 regional weather stations in northern Gansu, combined with conventional upper-air and surface observations as well as reanalysis physical quantity fields from the European Centre for Medium-Range Weather Forecasts (ECMWF), 104 typical cases of short-duration heavy rainfall from May to September during 2016–2019 were selected to conduct a mesoscale comprehensive analysis of the environmental conditions for the occurrence and development of short-duration heavy rainfall in northern Gansu, revealing some characteristics and patterns of such events in the region. The results indicate that: (1) Short-duration heavy rainfall in northern Gansu occurs mainly from June to August, with intensities mostly ranging from 10 to 20 mm. (2) The typical characteristics of short-duration heavy rainfall weather in northern Gansu can be classified into four flow patterns: subtropical high edge type, low-pressure trough type, northwesterly flow type, and Hetao blocking high type. (3) By analyzing the relationships and differences among different synoptic situations, categories, and physical quantity parameters, the circulation characteristics and physical quantity element indices and thresholds for various types of short-duration heavy rainfall weather were summarized. (4) Surface convergence lines (cold fronts) are the key systems triggering severe convective weather in northern Gansu, and the analysis of surface convergence lines (cold fronts) is crucial for nowcasting. (5) The northward movement of the low-level southerly jet (significant streamline) around 110°E and its convergence around 37°N are important criteria for determining whether short-duration heavy rainfall can occur in northern Gansu. The forecast performance for short-duration heavy rainfall in 2020 was also verified, achieving an accuracy rate of 63.6%, which demonstrates that the established short-duration heavy rainfall forecast indices possess strong predictive capability, thereby providing a new approach for improving the forecasting and warning capabilities for short-duration heavy rainfall.

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Full Text

Mesoscale Characteristics and Physical Quantity Configuration of Short-Time Heavy Rainfall in Northern Gansu Province

QIAN Li[1,2,3], ZHANG Chunyan[3], YANG Mei[3], LI Tianjiang[3]

[1]Lanzhou Institute of Arid Meteorology, Key Laboratory of Arid Climate Change and Disaster Reduction of Gansu Province (China Meteorological Administration), Lanzhou 730020, Gansu, China
[2]Key Laboratory for Cloud Physics of China Meteorological Administration, Beijing 100081, China
[3]Wuwei Meteorological Bureau, Wuwei 733000, Gansu, China

Abstract

Using precipitation data from 27 national automatic weather stations and 635 regional weather stations in northern Gansu Province, combined with conventional upper-air and surface observations as well as physical quantity fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, this study selected 104 typical cases of short-time heavy rainfall to conduct a mesoscale comprehensive analysis of the environmental conditions for the occurrence and development of short-time heavy rainfall events in northern Gansu. The results reveal several key characteristics and patterns of short-time heavy rainfall in this region: (1) Short-time heavy rainfall in northern Gansu is concentrated from June to August, with rainfall intensity predominantly ranging from 10–20 $mm \cdot h^{-1}$. (2) The typical characteristics of short-time heavy rainfall weather can be classified into four flow patterns: subtropical high marginal type, low-pressure trough type, northwest airflow type, and Hetao blocking high type. (3) By analyzing the relationships and distinctions among different weather situations, flow types, and physical parameters, the circulation characteristics and physical quantity thresholds for each type of short-time heavy rainfall are summarized. (4) The surface convergence line (cold front) represents the critical system triggering severe convective weather in northern Gansu, and its analysis is essential for short-term nowcasting. (5) The northward movement of the low-level southerly jet (significant streamline) to around 37°N and its convergence near 110°E serve as important indicators for determining whether short-time heavy rainfall will occur in northern Gansu. Verification of the 2020 short-time heavy rainfall forecast shows an accuracy rate of 63.6%, demonstrating that the established forecast indices have strong predictive capability and provide a new approach for improving short-time heavy rainfall forecasting and warning.

Keywords: short-time heavy rainfall; weather types; mesoscale analysis; physical quantity; element configuration

1. Introduction

Mesoscale analysis is a novel forecasting methodology based on component elements that evaluates high-impact weather systems causing severe convective weather by examining the configuration relationships among various elements to determine the location of severe convection. Since severe convective weather does not satisfy geostrophic balance constraints, mesoscale analysis employs extensive non-conventional meteorological data. By analyzing the configuration of moisture transport, instability conditions, and lifting mechanisms, this approach can effectively improve the accuracy of severe convective weather forecasting. In recent years, many scholars have attempted to use physical quantity thresholds for severe convective weather forecasting indicators. For example, Zhang Yiping et al. [?] analyzed convective weather characteristics in Henan using physical quantities, while Zhou Houfu et al. [?] utilized stability and energy indexes as short-term forecast indicators for severe convective weather. Numerous studies have proposed the "ingredients-based method" for forecasting severe convective weather. Doswell et al. [?] established the basic concept of the ingredients-based method, which provides forecasters with a clear forecasting framework for analyzing severe convective weather. Currently, many domestic scholars have conducted research on forecasting approaches for severe convective weather under different large-scale circulation backgrounds. Zheng Yuanyuan et al. [?] performed short-term nowcasting and warning research on severe convective weather under different large-scale circulation backgrounds. Xu Aihua et al. [?] studied the synoptic situation classification and basic element configuration characteristics of severe convective weather in central and eastern China. Bai Xiaoping et al. [?] investigated conceptual models of short-time heavy rainfall in eastern Northwest China.

Northern Gansu is located deep within the Eurasian continent, with scarce precipitation and annual rainfall ranging from 39.9 to 400.7 mm, representing typical arid and extremely arid regions. However, due to its location on the slope of the Tibetan Plateau, conditions are favorable for forming severe convective short-time heavy rainfall. The surface runoff generated by short-time heavy rainfall rapidly converges and flows down valleys, easily causing local flash floods, landslides, and debris flows with significant destructive potential. The unique topography and landforms result in strong local characteristics of heavy rainfall, and the sparse observation network makes short-time heavy rainfall forecasting particularly challenging. Qian Li et al. [?] studied the large-scale weather types causing heavy rain and hail in the eastern Hexi Corridor. Currently, research on mesoscale element configuration characteristics of short-time heavy rainfall in northern Gansu remains limited. This paper references the classification of severe convective weather in Gansu by Huang Yuxia et al. [?] and various conceptual models to select short-time heavy rainfall cases from severe convective weather in northern Gansu. Based on synoptic-scale classification, mesoscale element configuration thresholds for short-time heavy rainfall are constructed. Through comparative analysis, indicative forecasting indices with good predictive significance are summarized to improve the accuracy of short-time heavy rainfall forecasting and warning in this region.

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2. Data and Methods

2.1 Data Sources Precipitation data were selected from 27 national automatic weather stations and 635 regional weather stations in the study area for cases meeting the short-time heavy rainfall standard from May to September 2016–2019 (Beijing Time). The precipitation data underwent quality control through extreme value and temporal continuity checks, resulting in 104 valid short-time heavy rainfall cases. Historical upper-air and surface observations, as well as ECMWF reanalysis data (0.125°$×$0.125° resolution) at 08:00 and 20:00 BST daily, were utilized. Using the MICAPS 4.2 system weather analysis tools and mesoscale analysis toolboxes, and referencing the Technical Specification for Mesoscale Analysis of Severe Convective Weather in Gansu Province [**?**], synoptic and mesoscale analyses were performed for each short-time heavy rainfall case.

2.2 Study Area The study area is located in northern Gansu, including the jurisdictions of Jiuquan, Jiayuguan, Zhangye, Jinchang, Wuwei, Baiyin, and Lanzhou cities (Fig. 1). The region contains 27 national automatic weather stations and 635 regional weather stations.

2.3 Research Methods This study employs severe convective weather flow pattern identification and the ingredients-based forecasting method to analyze the morphological and physical quantity characteristics of short-time heavy rainfall in northern Gansu. The analysis focuses on moisture transport, lifting conditions, and instability conditions for deep convection development. Specifically: - **Moisture conditions** are represented by temperature-dewpoint difference below 700 hPa ($t_{700} - td_{700}$), pseudo-equivalent potential temperature (θ_{se700}), specific humidity (q_{700}), wet layer thickness, and low-level southerly jet. - **Lifting conditions** are represented by 500 hPa trough lines, 700 hPa low-level vortex shear lines, surface convergence lines, and low-level jet convergence lines. - **Instability conditions** are represented by vertical temperature distribution, humidity vertical distribution in short-time heavy rainfall areas, temperature difference between 500 hPa and 700 hPa ($t_{500} - t_{700}$), air mass index (K), Convective Available Potential Energy (CAPE), and 700 hPa vorticity (VOR700).

Mesoscale analysis charts provide configuration diagrams and thresholds for various key parameters. The 08:00 ECMWF numerical forecast reanalysis products were used to verify the short-time heavy rainfall forecast index thresholds in the region.

3. Results

3.1 Main Synoptic-Scale Flow Patterns of Short-Time Heavy Rainfall Processes Based on the 500 hPa circulation patterns, the 104 short-time heavy rainfall cases were classified into four synoptic types: subtropical high marginal type, low-pressure trough type, northwest airflow type, and Hetao blocking high type.

3.1.1 Subtropical High Marginal Type This type occurs most frequently during the main flood season in northern Gansu, accounting for 34.0% of total cases. It primarily appears from July to August, with frequency decreasing sharply from southeast to northwest. The subtropical high marginal type has two subtypes: (1) The 500 hPa subtropical high extends westward to 110°E, with its 5880 gpm contour reaching the Tianshui-Lanzhou line. The northwestern edge of the high maintains warm and moist airflow, while the central-western Hexi Corridor is controlled by a westerly trough. The area east of Zhangye is located at the intersection of the pre-trough southerly flow and the southwestern warm moist flow at the subtropical high edge, with short-time heavy rainfall falling in the convergence zone between the 5880 gpm line' s southwestern flow and the pre-trough southerly flow (Fig. 2a). (2) The Iranian high develops and moves eastward, while the subtropical high extends westward, forming a pronounced wind convergence zone between the two highs on the northeastern slope of the Tibetan Plateau. Combined with an eastward-moving westerly trough, the area east of Zhangye is located at the intersection of the pre-trough flow and the strong convergence between the two highs, with short-time heavy rainfall occurring in the convergence zone and the pre-trough southerly flow area (figure omitted). Since short-time heavy rainfall occurs at the edge of the subtropical high, these two subtypes are merged into one category.

3.1.2 Low-Pressure Trough Type This is the second most frequent type during the main flood season, accounting for 29.8% of cases. It occurs from June to August, with cumulative precipitation less than the subtropical high marginal type and frequency decreasing from east to west. At 500 hPa, a high-pressure ridge exists over eastern Hetao, with a low trough moving eastward and southward over Xinjiang and a southern branch trough developing over the Tibetan Plateau. The westerly trough and southern branch trough superimpose in phase on the northeastern slope of the Tibetan Plateau, forcing low-level moisture from the Bay of Bengal to transport northward. Cold and warm air converge over northern Gansu (Fig. 2b), with short-time heavy rainfall located ahead of the low trough.

3.1.3 Northwest Airflow Type This type ranks third in frequency, accounting for 27.9% of cases. It mostly occurs from afternoon to evening, is scattered, and is related to topography, with frequency decreasing from east to west. At 500 hPa, a low-pressure trough exists over eastern Hetao, while northern Gansu is controlled by northwest airflow from eastern Xinjiang, with a pronounced cold temperature trough. Due to strong cold advection at high altitudes and surface heating in the afternoon, short-time heavy rainfall is triggered.

3.1.4 Hetao Blocking High Type This is the least frequent type, accounting for 8.3% of cases. A blocking high is maintained over the Hetao region, with its ridge top extending northwestward. A southern branch trough develops over the Tibetan Plateau. The easterly flow at the base of the Hetao blocking high and the westerly flow in the westerlies form a low-vortex shear line over northern Gansu. The Hetao blocking high not only blocks the eastward movement of the low vortex at the ridge base, causing it to linger over northern Gansu for extended periods, but also blocks the transport of warm moist airflow to higher latitudes, creating a strong moisture convergence zone over northern Gansu (Fig. 2c).

3.2 Mesoscale Physical Element Configuration of Main Circulation

3.2.1 Subtropical High Marginal Type Short-time heavy rainfall of this type occurs in the southwestern flow ahead of the westerly trough (or in the shear line between the Tibetan high and subtropical high), accompanied by low-level shear lines or low-vortex human-shaped shear lines, with surface convergence lines triggering short-time heavy rainfall. The rainfall area is located in the right side of the upper-level northerly jet entrance region and in the convergence zone between low-level southerly and northerly jets (significant streamlines). A deep moist layer exists below 700 hPa, with the short-time heavy rainfall area surrounded by a moisture tongue where $t_{700} - td_{700} \leq 4$°C, $q_{700} \geq 7$ g · kg^{-1}, and $\theta_{se700} \geq 60$°C. Moisture flux convergence exists with $qfdiv700 \leq -2$ g · hPa^{-1} · cm^{-2} · h^{-1}, indicating good moisture conditions. The area exhibits strong vertical wind shear and an unstable stratification with cold upper and warm lower layers, $t_{500} - t_{700} \geq 30$°C, and CAPE\$ $29J \cdot kg$^{-1}\$, with upstream $t_{500} \geq$ 20°C and VOR700\$ 2×10^{-5}\$ s^{-1}. This type can produce short-time heavy rainfall with certain instability conditions due to good moisture conditions.

3.2.2 Low-Pressure Trough Type Short-time heavy rainfall occurs ahead of the westerly trough, with 500 hPa shear lines or low vortices, and 700 hPa low-vortex human-shaped shear lines. Surface cold fronts trigger short-time heavy rainfall. The rainfall area is located on the left side of the upper-level westerly jet exit region and ahead of the low-level southerly jet (significant streamline). A deep moist layer exists in the mid-lower levels, with the short-time heavy rainfall area surrounded by a moisture tongue where $t_{700} - td_{700} \leq 4$°C, $q_{700} \geq 7$ g · kg^{-1}, and $\theta_{se700} \geq 60$°C. Moisture flux convergence exists with $qfdiv700 \leq -2$ g · hPa^{-1} · cm^{-2} · h^{-1}, indicating good moisture conditions but less than the subtropical high marginal type. Strong vertical wind shear and an unstable stratification with cold upper and warm lower layers exist, with $t_{500} - t_{700} \geq$ 30°C, CAPE$ 20$J \cdot kg^{-1}, upstream $t_{500} \geq$ 20°C, and VOR700$ 5×10^{-5}$ s^{-1}. Both moisture and lifting conditions favor short-time heavy rainfall.

3.2.3 Northwest Airflow Type Short-time heavy rainfall occurs in the cold advection zone of northwest airflow, with 700 hPa shear lines and surface convergence lines. Afternoon thermal convection development triggers short-time heavy rainfall. The rainfall area is located in the right side of the upper-level northerly jet entrance region and in the convergence zone between low-level southerly and northerly jets (significant streamlines). A moist layer exists in the 700–850 hPa layer, with the short-time heavy rainfall area surrounded by a moisture tongue where $t_{700} - td_{700} \leq 7$°C, $q_{700} \geq 5$ g·kg^{-1}, and $\theta_{se700} \geq 52$°C. Moisture flux convergence exists with $qfdiv700 \leq -1$ g·hPa^{-1}·cm^{-2}·h^{-1}, representing the weakest moisture conditions among the four types. Strong cold advection exists at 500 hPa, with pronounced warm ridge characteristics at 700 hPa, creating an unstable stratification with cold upper and warm lower, dry upper and moist lower layers. Strong vertical wind shear exists between high and low levels, with CAPE$ 40$J \cdot kg^{\{-1\}, VOR700\ 2\times10}${-5}$ s^{-1}, and upstream $t_{500} \geq$ 20°C. Although moisture conditions are the weakest, strong thermal instability can still trigger short-time heavy rainfall under afternoon thermal conditions and topographic lifting.

3.2.4 Hetao Blocking High Type Short-time heavy rainfall occurs in the low vortex at the base of the Hetao blocking high, with 700 hPa low-vortex human-shaped shear lines and surface convergence lines triggering short-time heavy rainfall. The rainfall area is located in the right side of the upper-level westerly jet entrance region or in the divergence zone, and ahead of the low-level southerly jet (significant streamline). A deep moist layer exists in the 500–850 hPa layer, with the short-time heavy rainfall area surrounded by a moisture tongue where $t_{700} - td_{700} \leq 4$°C, $q_{700} \geq 8$ g·kg^{-1}, and $\theta_{se700} \geq 55$°C. Moisture flux convergence exists with $qfdiv700 \leq -1$ g·hPa^{-1}·cm^{-2}·h^{-1}. Due to the deep low vortex and strong convergence upward motion, the positive vorticity value is the largest among the four types, with VOR700$ 12×10^{-5}$ s^{-1}, CAPE$ 50$J \cdot kg^{-1}, upstream $t_{500} \geq$ 20°C, and $t_{500} - t_{700} \geq$ 32°C. This type features sustained moisture input and strong upward motion, resulting in long-duration short-time heavy rainfall.

The mesoscale physical quantity thresholds for the main circulation patterns are summarized in Table 1.

3.3 Typical Case Analysis Typical cases were selected based on representative large-scale circulation patterns, good coordination among moisture, instability, and lifting conditions in the environmental field, and numerous short-time heavy rainfall stations with strong hourly rainfall intensity.

3.3.1 Subtropical High Marginal Type The regional short-time heavy rainfall event on July 26, 2018, in Wuwei, Lanzhou, and Baiyin cities was a typical subtropical high marginal type. Within the region, 39 observation stations recorded daily precipitation \$ \$30 mm, and 15 stations recorded hourly rainfall intensity \$ $10mm \cdot h^{\text{\{-1\}}, withthemaximumhourlyintensityof39.8mm \cdot h}$\{-1\}\$ occurring at Xujiamo Village, Yongdeng County, Lanzhou City at 12:00. Mesoscale analysis shows that all physical quantities met or exceeded the thresholds for this type (Table 2). The main reason for the numerous stations and strong rainfall was abundant moisture supply from both the South China Sea and the Bay of Bengal, strong moisture flux convergence, and dry cold air intrusion that increased stratification instability.

3.3.2 Low-Pressure Trough Type The regional short-time heavy rainfall event on August 2, 2018, east of Zhangye City was a typical low-pressure trough type. Within the region, 25 observation stations recorded daily precipitation \$ \$30 mm, and 11 stations recorded hourly rainfall intensity \$ $10mm \cdot h^{\text{\{-1\}}, withthemaximumhourlyintensityof39.8mm \cdot h}$\{-1\}\$ occurring at Huishizhen, Huining County, Baiyin City at 08:00. Mesoscale analysis shows that all physical quantities met or exceeded the thresholds for this type (Table 2). The strong rainfall resulted from abundant moisture from the Bay of Bengal and the Bohai Sea, with dynamic lifting by a cold front increasing stratification instability.

3.3.3 Northwest Airflow Type The regional short-time heavy rainfall event on July 31, 2019, in northern Gansu was a typical northwest airflow type. Within the region, 32 observation stations recorded daily precipitation \$ \$30 mm, and 13 stations recorded hourly rainfall intensity \$ $10mm \cdot h^{\text{\{-1\}}, withthemaximumhourlyintensityof61.2mm \cdot h}$\{-1\}\$ occurring at Gankou, Sunan County, Zhangye City at 15:00. Mesoscale analysis shows that all physical quantities met or exceeded the thresholds for this type (Table 2). The numerous stations and strong rainfall resulted from abundant moisture from both the South China Sea and Bay of Bengal, strong vertical wind shear, and an upper-cold-lower-warm stratification that enhanced thermal instability.

3.3.4 Hetao Blocking High Type The regional short-time heavy rainfall event on August 6, 2019, in Jiuquan and Zhangye cities was a typical Hetao blocking high type. Within the region, 28 observation stations recorded daily precipitation \$ \$30 mm, and 12 stations recorded hourly rainfall intensity \$ $10mm \cdot h^{\text{\{-1\}}, withthemaximumhourlyintensityof25.3mm \cdot h}$\{-1\}\$ occurring at Shuanghu, Shandan County, Zhangye City at 20:00. Mesoscale analysis shows that all physical quantities met or exceeded the thresholds for this type (Table 2). The numerous stations and strong rainfall resulted from abundant moisture supply, with low-level southerly airflow reaching jet standards. The easterly flow at the base of the Hetao blocking high formed strong cyclonic convergence with the southerly flow, creating VOR700\$ 12×10^\{-5\}\$ s^{-1} and strong convergence upward motion.

3.4 Distribution Characteristics of Short-Time Heavy Rainfall During the main flood season (May–September) from 2016–2019, stations with hourly rainfall intensity (Q) $ 10mm·h^{-1}$ totaled 108, accounting for 44.4% of cases; Q$ 15mm·h^{-1}$ accounted for 23.3%; Q$ 20mm·h^{-1}$ accounted for 13.5%; and Q$ 25mm · h^{-1}$ accounted for 18.8%. This indicates that hourly rainfall intensity in northern Gansu is mostly 10-20 mm · h^{-1}. The temporal distribution shows that short-time heavy rainfall occurs most frequently from 06:00–18:00, with the peak period from 09:00–12:00 (Fig. 5). Monthly distribution shows the highest frequency in July (29.8% of cases), followed by August (27.9%). The main flow patterns by month are: May–low-pressure trough and northwest airflow types; June–subtropical high marginal and Hetao blocking high types; July–subtropical high marginal and low-pressure trough types; August–subtropical high marginal and Hetao blocking high types; and September–northwest airflow and Hetao blocking high types (Fig. 6).

Spatial distribution characteristics (Table 3) show the highest frequency in Lanzhou City (32.6%), followed by Baiyin City (30.2%), with the lowest in Jiuquan City (4.6%), decreasing sharply from east to west. Local type distributions: Lanzhou and Baiyin cities are dominated by the subtropical high marginal type; Wuwei City by the low-pressure trough type; Zhangye City by the low-pressure trough type; Jinchang City by the northwest airflow type; Jiayuguan City by the northwest airflow and Hetao blocking high types; and Jiuquan City by the Hetao blocking high type.

3.5 Forecast Index Verification From May–September 2016–2019, 104 short-time heavy rainfall cases occurred: 35 subtropical high marginal type, 31 low-pressure trough type, 29 northwest airflow type, and 9 Hetao blocking high type. Using ECMWF 24-hour forecast field physical quantity data, the forecast indices were verified against the mesoscale physical quantity thresholds. When all thresholds were satisfied, a short-time heavy rainfall process was forecasted. If multiple consecutive forecast times indicated short-time heavy rainfall, only one event was recorded. The system forecasted 77 short-time heavy rainfall events, with 49 correct forecasts, achieving an accuracy rate of 63.6%. False alarms totaled 28 events: 12 for subtropical high marginal type, 10 for low-pressure trough type, and 6 for northwest airflow type. Missed forecasts totaled 26 events, all northwest airflow type, primarily due to unsatisfied moisture conditions. Analysis revealed that for false alarms, surface convergence line passage occurred at night (21:00–04:00), when thermal conditions weaken and suppress short-time heavy rainfall development despite satisfied threshold conditions. The high false alarm rate for northwest airflow type indicates the importance of topographic lifting and local thermal uplift in short-time heavy rainfall occurrence. The missed forecasts suggest that with sufficient thermal and dynamic lifting conditions, short-time heavy rainfall can still occur even when moisture conditions are not fully satisfied.

4. Conclusions

(1) Short-time heavy rainfall in northern Gansu is concentrated from June to August, accounting for 81.7% of total cases. Rainfall intensity is predominantly 10–20 mm · h^{-1} (67.7% of cases). The subtropical high marginal type occurs most frequently (34.0% of cases).

(2) The key system for subtropical high marginal type short-time heavy rainfall is the subtropical high maintaining west of 110°E for extended periods, combined with dry cold air intrusion; or the Iranian high moving eastward to form a strong convergence zone on the northern slope of the Tibetan Plateau. On mesoscale analysis charts, the north side of the 5840 gpm line at 500 hPa is accompanied by shear lines or low-vortex human-shaped shear lines, with surface convergence lines triggering short-time heavy rainfall. This type features abundant moisture supply, relatively concentrated rainfall areas, long duration, and large cumulative precipitation, representing the main weather type causing extreme precipitation in Lanzhou and Baiyin cities.

(3) The key system for low-pressure trough type short-time heavy rainfall is the in-phase superposition of westerly and southern branch troughs on the northeastern slope of the Tibetan Plateau. On mesoscale analysis charts, 500 hPa has shear lines or low-vortex human-shaped shear lines, with low-level southerly and northerly jets (significant streamlines) converging over northern Gansu, and surface cold fronts triggering short-time heavy rainfall. This type features strong vertical wind shear and an unstable stratification with cold upper and warm lower layers, with large precipitation areas but short duration.

(4) The key system for northwest airflow type short-time heavy rainfall is strong dry cold advection at high altitudes. On mesoscale analysis charts, the temperature trough and dry tongue behind the upper-level trough are pronounced, with shear lines at 700 hPa, surface convergence lines, and convergence zones between low-level southerly and northerly jets (significant streamlines). Moisture conditions are the weakest among the four types, with only a low-level moist layer. However, strong cold advection at 500 hPa and pronounced warm ridge characteristics at 700 hPa create an unstable stratification with cold upper and warm lower, dry upper and moist lower layers. Strong vertical wind shear and a relatively strong thermal instability environment trigger short-time heavy rainfall, which occurs in the afternoon to evening as scattered events related to topography, without extreme precipitation characteristics.

(5) The key system for Hetao blocking high type short-time heavy rainfall is a high-pressure ridge maintained over the Hetao region with its top extending northwestward. This ridge both blocks the eastward movement of the

low vortex at its base, causing it to linger over northern Gansu, and blocks the transport of warm moist airflow to higher latitudes, creating a strong moisture convergence zone over northern Gansu. On mesoscale analysis charts, 700 hPa has low-vortex human-shaped shear lines with surface convergence line coordination. The rainfall area is located in the convergence zone among low-level southerly, easterly, and westerly jets (significant streamlines). This type features a deep moist layer and strong convergence upward motion, with the largest positive vorticity values among the four types. Due to sustained moisture input and strong upward motion, this type produces long-duration short-time heavy rainfall and is the primary weather type causing extreme precipitation in the Hexi Corridor.

(6) Literature review indicates that the main conditions for short-time heavy rainfall are convective instability and forced lifting from mesoscale and small-scale weather systems. The surface convergence line (cold front) is the critical system triggering severe convective weather in northern Gansu, and its analysis is crucial for short-term nowcasting. Due to the blocking effect of the Tibetan Plateau, moisture depletion after crossing the plateau makes moisture conditions the primary constraint for precipitation formation in this region. Therefore, in addition to convective instability and forced lifting mechanisms, moisture conditions become the key factor determining whether short-time heavy rainfall will occur. The northward movement of the low-level southerly jet (significant streamline) to around 37°N and its convergence near 110°E are important indicators for short-time heavy rainfall occurrence in northern Gansu.

It should be noted that this study selected 104 cases to classify and analyze short-time heavy rainfall weather types, which is a relatively small sample size. The universality of these results requires further validation and refinement through additional cases. Moreover, since severe convective weather is primarily triggered by mesoscale and small-scale systems, integrating radar data and mesoscale model data into the forecasting model will be the focus of future research.

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