Circulation Patterns and Low-Level Jet Characteristics of 20 Heavy Rainfall Events on the Eastern Foothills of Helan Mountain: Postprint

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Abstract

The eastern foothills of Helan Mountain constitute one of the extreme heavy rain-prone regions in Northwest China. To further investigate the atmospheric circulation configuration and evolution characteristics of low-level jet systems during heavy rain events in this region, and to improve the accuracy of heavy rain forecasting as well as disaster prevention and mitigation capabilities, this study employs dense surface precipitation observation data and NCEP/NCAR reanalysis data to conduct a comprehensive analysis of the formation mechanisms of 20 heavy rain events in the eastern foothills of Helan Mountain from 2009 to 2020. The results indicate that: (1) Based on the 500 hPa circulation pattern characteristics, the 20 heavy rain processes in this region can be classified into pre-upper-level trough type and northwest side of Western Pacific subtropical high type. Pre-upper-level trough type precipitation occurs and maintains under the influence of upper-level westerly troughs, in conjunction with upper-level jets and low-level water vapor convergence fields. During the northwest side of subtropical high type precipitation process, the eastern foothills of Helan Mountain are situated on the northwest side of the Western Pacific subtropical high, with the edge of the subtropical high bringing abundant water vapor, and the cooperation of upper and lower level dynamic convergence rendering this type of precipitation more intense. (2) Significant differences exist in the low-level jet systems corresponding to the two types of precipitation processes. For the northwest side of subtropical high type precipitation, its low-level jet exhibits characteristics of northward advancement and intensification followed by southward retreat and weakening, with the jet axis located on the left side of the Helan Mountain body, playing roles such as water vapor transport and increasing wind speed on the windward slope during the heavy rain process. (3) During pre-upper-level trough type precipitation processes, the low-level jet mostly exhibits eastward movement and weakening characteristics, with the jet

axis located on the right side of the mountain body; the development and evolution of mesoscale cyclones generated by the dynamic effects of the low-level jet play an important role in triggering and maintaining this type of heavy rain.

Full Text

Preamble

Circulation Patterns and Low-Level Jet Characteristics of 20 Heavy Rainfall Events in the Eastern Piedmont of the Helan Mountains

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Abstract: The eastern piedmont of the Helan Mountains represents one of Northwest China' s most vulnerable regions to extreme rainstorms. To further investigate the atmospheric circulation configurations and evolution characteristics of low-level jet (LLJ) systems during rainstorm events, and to improve forecast accuracy and disaster mitigation capabilities in this region, this study comprehensively analyzed the formation mechanisms of 20 heavy rainfall events in the eastern Helan Mountains from 2009 to 2020 using high-resolution surface precipitation observations and NCEP/NCAR reanalysis data. The results indicate that based on 500 hPa circulation patterns, these 20 rainstorm events can be classified into two categories: "in front of upper trough" and "northwest side of the subtropical high." The "in front of upper trough" type occurs under the influence of upper-level westerly troughs, coupled with upper-level jets and low-level water vapor convergence fields. During the "northwest side of the subtropical high" events, the eastern Helan Mountains are situated on the northwestern flank of the western Pacific subtropical high, whose periphery transports abundant moisture, and the combined dynamic convergence at upper and lower levels intensifies precipitation. Significant differences exist in the corresponding LLJ systems: the "northwest side of the subtropical high" type exhibits northward intensification and southward retreat/weakening, with the jet axis primarily located on the left side of the Helan Mountains, playing crucial roles in moisture transport and enhancing windward slope velocities. The "in front of upper trough" type displays eastward movement and weakening characteristics, with the jet axis on the right side of the mountains, where mesoscale cyclone development driven by LLJ dynamics critically triggers and maintains these rainstorms.

Keywords: heavy rainfall; low-level jet; circulation pattern; composite analysis; eastern Helan Mountains

1 Data and Methods

1.1 Data and Methodology

This study employs synoptic and composite analysis methods to statistically examine the circulation patterns and LLJ characteristics of heavy rainfall events in the eastern Helan Mountains from 2009 to 2020. The dataset includes: (1) high-resolution precipitation observations from 宁夏' s automated weather stations during the 20 selected rainstorm events, which have undergone quality control; and (2) NCEP FNL (Final Operational Global Analysis) data with 1°$×$1° horizontal resolution and 6-hour temporal intervals. Composite analyses were performed for pre-rainfall (using the most recent data before precipitation onset) and post-rainfall (using the most recent data after precipitation ended) circulation and moisture fields, along with precipitation distribution composites derived from the dense observation network.

For LLJ statistics, considering the actual terrain distribution around Ningxia, this study defines LLJs as maximum wind speed zones exceeding 12 $m \cdot s^{-1}$ within 500 km of the Helan Mountains' eastern piedmont at the 700 hPa isobaric level. Recognizing that easterly flows significantly impact Northwest China precipitation, strong wind belts with speeds $ $10m \cdot s^{-1} were also analyzed. The LLJ center position nearest to the rainstorm center was calculated, with jet movement speed derived from the average positional variability of jet centers during precipitation events. Jet trajectories were obtained by connecting jet center positions at 6-hour intervals and applying smoothing. All times referenced in this study are Beijing Time.

1.2 Precipitation Distribution Characteristics

According to the national rainstorm disaster grading standard (GB/T 33680-2017) implemented on December 1, 2017, a rainstorm event is defined as a precipitation process where at least one station records cumulative rainfall $ $50 mm. Based on this criterion, 20 representative rainstorm cases with relatively complete data were selected for the eastern Helan Mountains. The precipitation centers of these 20 cases are distributed relatively uniformly along the eastern slopes of the Helan Mountains [Figure 1: see original paper]. Most centers are located immediately adjacent to the mountain' s eastern side, where terrain-forced uplift of the windward slope significantly enhances precipitation. However, four cases show precipitation centers relatively distant from the mountain, less influenced by terrain, representing large-scale precipitation processes.

Analysis of the diurnal variation characteristics reveals that the average precipitation peak occurs primarily during 20:00–08:00, with a secondary peak during 12:00–16:00. The nocturnal precipitation peak is more pronounced, indicating that rainstorms in the eastern Helan Mountains predominantly occur in the afternoon and nighttime, with nighttime characteristics being particularly evident.

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2 Circulation Background of Two Rainstorm Types

2.1 "In Front of Upper Trough" Type Circulation Analysis

Among the 20 cases, 11 belong to the "in front of upper trough" category. Composite analysis shows a favorable circulation pattern with high pressure in the east and low pressure in the west at 500 hPa. Before precipitation [Figure 2a: see original paper], a westerly trough exists aloft, with Ningxia located ahead of the trough. As the trough moves eastward, dry cold air descending behind the trough converges with warm moist airflow from the northeastern Tibetan Plateau, creating favorable conditions for precipitation. This shortwave trough in the mid-troposphere serves as the primary influencing system.

At 200 hPa [Figure 2c: see original paper], the South Asian High appears elliptical with its eastern ridge point near 105°E. The Helan Mountains are situated on the right side of the upper-level jet entrance region and along the periphery of the South Asian High. The secondary circulation induced by the jet entrance region enhances low-level convergence and upward motion, providing favorable dynamic conditions. Strong precipitation requires abundant moisture transport. The 850 hPa moisture flux composite reveals a strong water vapor convergence center over the eastern Helan Mountains [Figure 3a: see original paper], with southeasterly flow east of Ningxia supplying moisture for this rainstorm type.

During the later precipitation stage, as the westerly trough moves eastward [Figure 2b: see original paper], moisture convergence weakens significantly [Figure 3b: see original paper], and the upper-level jet weakens. Ningxia becomes controlled by subsidence rather than upward motion, making the large-scale circulation unfavorable for precipitation maintenance, and the event gradually ends. The duration of this rainstorm type (10–30 hours) correlates with the movement speed of the shortwave trough, with cumulative precipitation generally ranging from 80–120 mm.

2.2 "Northwest Side of the Subtropical High" Type Circulation Analysis

Nine cases resulted from subtropical high activity. Composite analysis shows that before precipitation, the 500 hPa 586 dagpm contour' s western ridge point is located near 105°E [Figure 4a: see original paper]. The Helan Mountains are positioned on the northwestern side of the subtropical high, where southward-moving cold air converges with warm moist air from the subtropical system along the eastern piedmont, favoring severe convective weather development.

At 200 hPa [Figure 4c: see original paper], the South Asian High' s eastern ridge point is near 120°E, with the high center exceeding 1260 dagpm—significantly eastward and stronger than in the "in front of upper trough" type, characteristic of an eastern-type South Asian High. When the South Asian High assumes an eastern pattern, Ningxia lies along the high-pressure center' s periphery with strong upper-level divergence that enhances low-level upward motion. Combined with the subtropical high' s westward extension and northward jump, this configuration promotes rainstorm triggering and maintenance. The stronger, more easterly South Asian High also produces a more intense upper-level jet, with Ningxia located on the jet' s right side. Momentum transfer from aloft creates low-level wind shear and convergence, further intensifying precipitation.

Moisture convergence at 850 hPa is substantially stronger in this type [Figure 5a: see original paper] compared to the "in front of upper trough" type, and remains robust even during the precipitation' s end stage [Figure 5b: see original paper]. As the subtropical high retreats eastward and its control area shrinks, the precipitation process concludes. This rainstorm type occurs under favorable circulation conditions created by the subtropical high's advance and retreat. The maximum process rainfall can exceed 250 mm, significantly exceeding the "in front of upper trough" type. Such short-term extreme precipitation in Ningxia' s arid and semi-arid regions often causes more severe disasters.

These analyses demonstrate that heavy rainfall in the eastern Helan Mountains requires favorable large-scale circulation backgrounds. The eastward movement of westerly troughs and the advance/retreat of the subtropical high system determine the convergence zones of cold and warm air masses and the characteristics of LLJ systems, leading to differences in precipitation distribution and intensity between the two rainstorm types [Figure 6: see original paper]. The "in front of upper trough" circulation background primarily corresponds to large-scale precipitation processes across northern Ningxia, while the "northwest side of the subtropical high" background produces terrain-induced rainstorms along the Helan Mountains with much greater intensity .

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3 Low-Level Jet Characteristics in Two Rainstorm Types

3.1 Relationship Between LLJ and Precipitation Intensity

Statistical analysis of LLJ characteristics in Ningxia reveals that southerly jets in southern Ningxia are closely associated with summer rainstorms in the eastern Helan Mountains. These jets typically appear as narrow north-south oriented zones at 700 hPa with wind speeds $ 10$m \cdot s^{-1}. Although the jet centers are located relatively far from the Helan Mountains, their northern endpoints are generally near 106°E in central Ningxia. When these strong wind belts encounter the Helan Mountains, terrain-forced uplift triggers and enhances precipitation.

Statistical relationships between jet intensity/movement and precipitation characteristics show strong correlations between southern Ningxia LLJs and precipitation intensity [Figure 7: see original paper]. Jet intensity exhibits excellent positive correlation with maximum hourly rainfall and maximum process rainfall [FIGURE:7b,c], where stronger jet center winds correspond to greater rainfall intensity and totals. Conversely, jet movement speed shows negative correlation with maximum hourly intensity [Figure 7a: see original paper]; slower-moving jets provide more stable moisture and energy transport, resulting in stronger precipitation.

Jet center wind speed statistics indicate that the "northwest side of the subtropical high" type produces stronger average and median jet center winds than the "in front of upper trough" type. The Helan Mountains' main peak is near 38.8°N, 106°E. Analysis of jet activity regions shows that "northwest side of the subtropical high" jets have average and median center latitudes greater than 38.8°N, positioning them closer to the mountains than "in front of upper trough" jets. The median jet center longitudes for both types are similar, but the "in front of upper trough" type shows greater dispersion, with centers mostly on the mountain's eastern side (relative to the 106°E peak), while "northwest side of the subtropical high" jets are more concentrated on the western side.

3.2 Relationship Between LLJ Activity and Rainstorm Location

Under favorable large-scale circulation conditions, precipitation location is closely related to mesoscale system evolution. LLJs represent important mesoscale systems in rainstorm processes. Throughout the lifecycle of the 20 selected cases, most were accompanied by LLJs of varying intensities and activity characteristics. LLJ formation and maintenance depend on coupling between upper and lower-level circulations and weather system forcing. Previous research indicates LLJs are associated with the northward jump of the western Pacific subtropical high and are closely related to frontogenesis, topographic waves, and lee cyclone development.

Composite precipitation analysis for the two circulation types reveals significant differences in both spatial distribution and intensity [Figure 8: see original paper]. The "northwest side of the subtropical high" type shows precipitation aligned north-south along the Helan Mountains [Figure 8a: see original paper], with average station cumulative rainfall exceeding 50 mm. Terrain-forced uplift along the mountain range amplifies precipitation. In contrast, "in front of upper trough" precipitation centers are mostly located to the right of the red dashed line [Figure 8a: see original paper], farther from the Helan Mountains with more dispersed distribution and weaker intensity (average station cumulative rainfall ~30 mm).

LLJ center positions and movement paths during the two rainstorm types show distinct characteristics [FIGURE:8b,c]. "Northwest side of the subtropical high" LLJs exhibit northward intensification and southward retreat/weakening, with some jets oscillating within small north-south ranges. These jets are primarily located on the left side of the Helan Mountains, oriented north-south, and play major roles in transporting abundant moisture and increasing windward slope wind speeds. "In front of upper trough" LLJs show eastward movement and weakening, oriented east-west, with the jet axis on the mountain's right side. The development and evolution of mesoscale cyclones generated by LLJ dynamics serve as important triggering and maintaining mechanisms for this rainstorm type.

Wind direction frequency analysis reveals further differences [Figure 10: see original paper]. The "northwest side of the subtropical high" type concentrates strongly on southerly jets (~70%), while the "in front of upper trough" type is more dispersed, with ~50% southerly jets and ~30% southwesterly jets. Considering the Helan Mountains' orientation, southerly jets intersect the mountain range at a larger angle than southwesterly jets, favoring stronger terrain-forced uplift. The higher proportion of southerly jets in the "northwest side of the subtropical high" type thus produces more pronounced terrain amplification effects.

Typical case analyses illustrate these differences clearly [Figure 11: see original paper]. For "northwest side of the subtropical high" cases, precipitation peaks generally occur after or during jet northward intensification, with hourly rainfall rates reaching 80–100 mm. Under the large-scale terrain of the Helan Mountains, LLJs encountering the mountain trigger gravity wave disturbances that play important roles in rainstorm initiation and enhancement, primarily through moisture transport and increased windward slope velocities. For "in front of upper trough" cases, the jet axis is located on the mountain's right side, showing convergence flow fields on the jet's left front that gradually affect the eastern Helan Mountains as the jet moves eastward. The development of mesoscale cyclones from LLJ dynamics provides crucial dynamic conditions for triggering and maintaining precipitation, with precipitation peaks appearing later in the jet's evolution.

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4 Discussion

This study comprehensively analyzed the relationships between circulation patterns, LLJ characteristics, and precipitation distributions for 20 heavy rainfall events in the eastern Helan Mountains from 2009 to 2020 using dense surface observations and NCEP reanalysis data. Previous research [5,7-8] has shown that radar observations near the Helan Mountains reveal wind speed zones exceeding 12 $m \cdot s^{-1}$. However, C-band radar products in Northwest China (including reflectivity, radial velocity, and spectral width) are primarily applied to precipitation distribution retrieval, mesoscale convective system analysis, and data assimilation, with radial velocity or retrieved wind fields mainly used to reflect internal flow structures at different convective system development stages. Quality issues remain in wind fields retrieved under different assumptions and constraints, so this study did not utilize Ningxia radar data to analyze LLJ characteristics or gravity wave effects on rainstorms.

Additionally, the analysis of LLJ impacts on precipitation is primarily based on fundamental atmospheric dynamics theory, without in-depth investigation into the specific mechanisms affecting rainstorm location and intensity in the eastern Helan Mountains. This represents a direction for future research.

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5 Conclusions

Using dense station precipitation observations and NCEP 1°$×$1° reanalysis data, this study conducted statistical and composite analyses of 20 heavy rainfall cases in the eastern Helan Mountains from 2009 to 2020. The main conclusions are:

1) Heavy precipitation centers of the selected cases are relatively uniformly distributed along the eastern Helan Mountains, with precipitation primarily occurring from afternoon to nighttime. Based on 500 hPa circulation patterns, these events can be classified into "northwest side of the subtropical high" and "in front of upper trough" types. The "in front of upper trough" type is primarily influenced by eastward-moving westerly troughs, while the "northwest side of the subtropical high" type occurs under favorable moisture transport conditions along the subtropical high' s periphery.
2) The "in front of upper trough" type develops under the influence of 500 hPa troughs, coupled with 200 hPa jets and 850 hPa moisture convergence. The "northwest side of the subtropical high" type features the rainstorm area on the right side of the upper-level jet axis, with an eastern-type South Asian High. The combined dynamic convergence at upper and lower levels is more significant, and abundant moisture from the subtropical high' s edge produces stronger precipitation intensity.
3) LLJs with different activity characteristics exist in southern Ningxia, showing good correspondence with precipitation features. The "northwest side of the subtropical high" LLJs exhibit northward intensification and southward retreat/weakening, while "in front of upper trough" LLJs show eastward movement and weakening. The jet axis of the former is located on the left side of the Helan Mountains, primarily transporting moisture and increasing windward slope wind speeds. The latter' s jet axis is on the mountain's right side, where mesoscale cyclone development driven by LLJ dynamics plays a crucial role in triggering and maintaining precipitation.

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