Postprint: Characteristic Analysis of Mesoscale Convective Systems in the "6·14" Extreme Rainstorm Event on the Northern Slope of the Kunlun Mountains

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Abstract

Against the backdrop of global warming, extreme rainstorms occur frequently on the northern slope of the Kunlun Mountains with substantial impacts. Due to the relative scarcity of observations and research on these events, monitoring and forecasting rainstorms in this region is challenging. Understanding their occurrence mechanisms and key influencing systems constitutes an effective approach for improving monitoring and forecasting capabilities, which is of great significance for disaster prevention and mitigation in this region. Utilizing high spatiotemporal resolution meteorological observation data, GPS/Met precipitable water vapor (PWV) data, Fengyun satellite data (FY-2H), and ERA5 reanalysis data, this study conducts an analysis of the large-scale circulation background and characteristics of mesoscale convective systems for an extreme rainstorm event that occurred on the northern slope of the Kunlun Mountains from June 14–17, 2021. The results indicate: (1) This rainstorm process was characterized by numerous rainstorm stations, large cumulative precipitation, strong locality, and high extremity. Three extreme rainstorm centers emerged in the Hotan region, where short-duration heavy rainfall and continuous precipitation occurred respectively. The short-duration heavy rainfall process featured brief duration, with maximum hourly rainfall intensity reaching 29.4 mm; the continuous precipitation lasted for 3 days, with hourly rainfall intensity less than 5 mm. The favorable circulation background for this extreme rainstorm event was the maintenance of a dipole-pattern South Asian high in the upper troposphere and the formation and development of a Central Asian low vortex. Under the combined influence of upper- and lower-level jets, strong upper-level divergence and lower-level convergence promoted the development of atmospheric vertical motion, while the coordinated configuration of southerly airflow at 500 hPa, a shear line at 700 hPa, and easterly airflow at 850 hPa provided favorable dynamic conditions for the rainstorm. (2) Water vapor transport in the middle troposphere was dominated by southwestern and southwestern+southern pathways, while in the lower troposphere it was primarily carried by low-level easterly jets. The coupling of water vapor transport pathways between the middle and lower troposphere promoted the development and intensification of this extreme rainstorm. Sustained water vapor transport and a strong water vapor flux convergence center prior to the extreme rainstorm event led to a significant moistening and accumulation process in the precipitable water vapor (PWV) over the rainstorm area before precipitation, with PWV reaching 30 mm. (3) Train-effect and merger-intensification type mesoscale convective cloud clusters continuously generated, developed, and passed over the rainstorm stations, serving as the direct influencing system that triggered short-duration heavy rainfall, with stations located where the blackbody brightness temperature (TBB) gradient of the convective cloud clusters was maximal. The development and maintenance of meso-β and meso-α scale convective cloud clusters, along with the persistent coverage of vortex-shaped mesoscale convective cloud belts, constituted the key systems responsible for continuous precipitation at the rainstorm stations.

Full Text

Preamble

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Mesoscale Convective System Characteristics of the "6 • 14" Extreme Rainstorm Process on the Northern Slope of the Kunlun Mountains

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Abstract: Against the backdrop of global warming, extreme rainstorms occur frequently on the northern slope of the Kunlun Mountains with significant impacts. However, due to relative scarcity of observations and research, monitoring and forecasting of rainstorms in this region remain challenging. Understanding their occurrence mechanisms and key influencing systems is an effective approach to improve monitoring and forecasting capabilities, which is of great significance for disaster prevention and mitigation in the region. Using high temporal-spatial resolution meteorological observations, GPS/Met atmospheric precipitable water vapor (PWV) data, Fengyun satellite data (FY-2H), and ERA5 reanalysis data, this study analyzes the large-scale circulation background and mesoscale convective system characteristics of an extreme rainstorm process on the northern slope of the Kunlun Mountains from June 14–17, 2021. The results show that: (1) This rainstorm event featured numerous rainstorm stations, large cumulative precipitation, strong locality, and extreme intensity, with three extreme rainstorm centers occurring in the Hotan region, where short-duration heavy precipitation and continuous precipitation occurred respectively. The short-duration heavy precipitation process was brief, with maximum hourly rainfall intensity reaching 29.4 mm, while continuous precipitation lasted for 3 days with hourly intensity below 5 mm. The favorable circulation background for this extreme rainstorm was the maintenance of a dual-body South Asian high in the upper troposphere and the formation and development of a Central Asian low vortex. Under the combined action of upper- and lower-level jets, strong upper-level divergence and lower-level convergence promoted vertical atmospheric motion development. The 500 hPa southerly flow, 700 hPa shear line, and 850 hPa easterly flow cooperated to provide favorable dynamic configuration for the rainstorm. (2) Water vapor transport in the middle troposphere was dominated by southwest and southwest-south paths, while the lower layer was dominated by low-level easterly jets. The coupling of water vapor transport paths between middle and lower layers promoted the development and intensification of this extreme rainstorm. Continuous water vapor transport and strong water vapor flux convergence centers before the extreme rainstorm caused the atmospheric precipitable water vapor (PWV) in the rainstorm area to show significant moistening and accumulation processes before precipitation, with PWV reaching 30 mm. (3) Train-effect-type and merging-strengthening-type mesoscale convective cloud clusters continuously generated and moved over the rainstorm stations, serving as the direct influencing system triggering short-duration heavy precipitation, with stations located at the maximum gradient of the cloud clusters' blackbody brightness temperature (TBB). The development and maintenance of meso-β and meso-α scale convective cloud clusters and the continuous coverage of vortex-like mesoscale convective cloud bands were the key systems causing continuous precipitation at the rainstorm stations.

Keywords: extreme rainstorm; Central Asian low vortex; water vapor transport; mesoscale convective system; northern slope of the Kunlun Mountains

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Introduction

The Kunlun Mountains border the southern Xinjiang basin to the north, connect to the northern Tibetan Plateau to the south, and adjoin the Pamir Plateau to the west. The northern plain region of the mountain range has an average annual precipitation of only 25–50 mm. Research indicates that under global warming, both the frequency and intensity of heavy precipitation in Xinjiang show increasing trends, particularly for localized extreme events. Moreover, precipitation in southern Xinjiang has also increased, with more frequent heavy rain occurrences. Due to Xinjiang's fragile ecological environment, heavy rain often causes floods, mudslides, and landslides, posing serious threats to production, construction, and people's lives and property. Additionally, rainstorms are characterized by sudden onset and difficult forecasting, creating challenges for disaster prevention and mitigation efforts. Therefore, understanding the occurrence and development mechanisms of rainstorm processes in Xinjiang is crucial.

Previous studies have documented the spatiotemporal distribution characteristics of precipitation in Xinjiang, analyzing large-scale circulation backgrounds favorable for rainstorms, water vapor transport features, precipitation dynamic mechanisms, precipitation system structures, and numerical simulations, yielding numerous meaningful results. Regarding large-scale circulation backgrounds and synoptic systems, research has shown that most rainstorms in southern Xinjiang occur under the large-scale circulation pattern of a dual-body South Asian high. Studies indicate that the Central Asian low trough (vortex), West Siberian low trough (vortex), and low-level jet are the main systems affecting short-duration heavy precipitation in Xinjiang. Classification of short-duration heavy precipitation weather on the northern slope of the Kunlun Mountains reveals three types: Central Asian low vortex (trough) type, westerly short-wave type, and Tibetan Plateau low vortex (trough) type, with the Central Asian low vortex (trough) type being the most common. Cooperation between upper- and lower-level jets can provide favorable dynamic conditions for rainstorm occurrence. Research has found that low-level jets serve not only as water vapor channels for rainstorm locations in southern Xinjiang but also form strong convergence with topography, representing key factors triggering rainstorms and concentrating water vapor.

Regarding water vapor sources and transport pathways for rainstorms, studies show that water vapor for rainstorm processes in western southern Xinjiang mainly originates from Southwest Asia, Central Asia, the Mediterranean and Black Sea regions, and the Atlantic Ocean and its coastal areas. Research has found that the Central Asian low vortex carries water vapor eastward and southward, while low-latitude water vapor from the Bay of Bengal and Arabian Sea is transported northwestward, converging over western southern Xinjiang to trigger regional rainstorms. Mesoscale convective systems (MCS) are important weather systems causing disastrous rainstorm weather in summer. Studies indicate that after mesoscale convective cloud clusters form, they continuously move northward under the guidance of steering flow, serving as the direct system causing extreme rainstorms in western Xinjiang. Research has shown that convective storms affecting short-duration heavy precipitation in Xinjiang are mainly of merging-strengthening type, train-effect type, and local development type, with the merging-strengthening type being the most common and the train-effect type the least, primarily occurring on the northern slope of the Tianshan Mountains under topographic influence.

Local extreme weather disasters are often caused by uneven energy accumulation and topographic effects in the early stage, leading to secondary circulations that cooperate with synoptic-scale systems. Large-scale terrain transition zones are among the most important complex conditions affecting land-atmosphere interactions, whose dynamic and thermal effects not only generate strong mesoscale circulations affecting water vapor transport and weather process formation but also cause non-uniform dynamic disturbances within the atmospheric boundary layer, influencing the occurrence and development of convective activities. These research results help deepen understanding of extreme rainstorm occurrence and development mechanisms under Xinjiang's special topographic conditions. However, compared with central and eastern China, research on rainstorms in Xinjiang, especially on the northern slope of the Kunlun Mountains, remains relatively scarce and insufficiently in-depth. Moreover, due to Xinjiang's special terrain and large north-south precipitation differences within the region, it is necessary to conduct targeted analyses of typical cases.

From June 14–17, 2021, an extreme rainstorm process occurred on the northern slope of the Kunlun Mountains, significantly impacting local agricultural and pastoral production, transportation, and urban operations. This rainstorm featured large cumulative precipitation, numerous rainstorm stations, strong locality, and extreme intensity. What were the large-scale circulation background fields and key mesoscale systems that triggered this extreme rainstorm process? What were the water vapor transport characteristics and mesoscale convective system features causing this rainstorm? To address these questions, this paper uses multi-source datasets to analyze this extreme rainstorm process on the northern slope of the Kunlun Mountains, hoping to provide a theoretical basis for rainstorm monitoring, early warning, and disaster prevention and mitigation in this region.

1.1 Data

This study uses regional automatic station hourly precipitation data for precipitation analysis. Large-scale circulation background, mesoscale system, and water vapor transport characteristics are analyzed using ERA5 reanalysis data with 0.25°$×0.25°horizontalresolution.GPS/Metatmosphericprecipitablewatervapor(PWV)datafromHotanPre
2Hblackbodybrightnesstemperature(TBB)dataat30−minuteintervalswith0.1°×$0.1° horizontal resolution.

1.2 Methods

Figure 1 shows the topographic map of the northern slope of the Kunlun Mountains, revealing an obvious eastward-opening trumpet-shaped topography, with the West Tianshan Mountains to the northwest, Pamir Plateau to the west and southwest, Kunlun Mountains to the south, and Taklamakan Desert to the east, with some areas exceeding 4000 m in elevation. Note: Based on the standard map of Xinjiang Uygur Autonomous Department of Natural Resources with approval number Xinjiang S(2023)063, with no modifications to base map boundaries. The same applies below.

2.1 Weather Situation and Extremity

From 08:00 on June 14 to 20:00 on June 17, 2021, a heavy rainfall process occurred on the northern slope of the Kunlun Mountains, affecting Kashgar Prefecture, Kizilsu Kirghiz Autonomous Prefecture, and Hotan Prefecture in southern Xinjiang. The maximum rainfall center was at the Shangpulu Debris Flow Frequent Area Station (No. 1) in Luopu County, Hotan Prefecture, with cumulative precipitation of 121.6 mm, followed by the Buqiong Village Station (107.8 mm) and the Langan Township Kunlun Canal Head Station (102.1 mm). A total of 15 stations recorded short-duration heavy precipitation ($10.0mm \cdot h^{-1}$), with maximum hourly intensity reaching 29.4 mm. Further analysis of the temporal distribution of hourly precipitation at the three stations with maximum cumulative precipitation (Figure 2) shows that heavy precipitation at the Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County mainly occurred from 19:30 to 23:30; at the Langan Township Kunlun Canal Head Station mainly from 20:00 to 03:00; and at Buqiong Village Station, distinctly different from the first two stations, with significantly lower precipitation intensity but longer duration from 13:00 to 20:00.

This rainstorm process broke historical daily precipitation records at Luopu County (74.1 mm), Moyu County (59.6 mm), and Hotan City (56.0 mm), exceeding their annual average precipitation. Among them, the June 15 daily precipitation at Luopu County was 1.8 times the station's annual average precipitation. This rainstorm process featured large cumulative precipitation, numerous rainstorm stations, strong locality, and extreme intensity, causing significant impacts on local people's production and life.

2.2 Large-Scale Circulation Background

Figure 3 shows the large-scale circulation background and mesoscale systems for this precipitation process. The results indicate that at 100 hPa, the South Asian high transitioned from zonal to dual-body pattern, with centers over the Iranian Plateau and Tibetan Plateau (figure omitted). On June 14, the South Asian high continued to develop and strengthen, forming a mid-latitude subtropical long-wave trough between the high centers. After establishment, the southwest jet ahead of the long-wave trough strengthened and maintained, with the rainstorm area located in the strong divergence area to the right of the upper-level jet entrance, providing dynamic conditions for the rainstorm. At 500 hPa, the Iranian subtropical high developed and strengthened, superimposing with the Eastern European high-pressure ridge, with the Central Asian low trough continuously developing and extending southward ahead of the ridge (figure omitted). On June 15, as the Northwest Pacific subtropical high extended westward and northward and the Iranian high continued strengthening, the Central Asian low trough extended southward to the western part of southern Xinjiang, causing precipitation in western southern Xinjiang. Sandwiched between the Iranian high and the Western Pacific subtropical high, the Central Asian low trough developed into a Central Asian low vortex system, with the rainstorm area located east of the Central Asian low vortex. The southerly flow ahead of the Central Asian low vortex continuously transported warm, moist water vapor to the rainstorm area. At 700 hPa, a clear wind field shear line existed over the western part of the northern Kunlun Mountains slope between Lake Balkhash and the Aral Sea (figure omitted), which, combined with strong easterly flow at 850 hPa, facilitated water vapor accumulation in the northern Kunlun Mountains slope region, providing favorable moisture conditions for the rainstorm.

In summary, this extreme rainstorm process on the northern slope of the Kunlun Mountains occurred under a "two ridges and one trough" circulation background, with a dual-body South Asian high in the upper level and a developing Central Asian low vortex. The rainstorm area was located to the right of the 200 hPa southwest jet entrance, providing favorable dynamic conditions. The 500 hPa southerly flow, 700 hPa shear line, and 850 hPa easterly flow cooperated to provide favorable dynamic configuration for water vapor transport and accumulation in the rainstorm area, promoting the occurrence and development of this extreme rainstorm event.

2.3 Water Vapor Transport Characteristics

Rainstorm occurrence depends on adequate water vapor and continuous transport. Here we focus on analyzing water vapor flux and wind field spatial distribution at 500 hPa and 850 hPa for the three stations with maximum cumulative precipitation: Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County, Buqiong Village Station, and Langan Township Kunlun Canal Head Station. Figure 4 shows that at 500 hPa, the mid-latitude trough ahead of the southwest flow converged with the subtropical high's southerly flow on the southwestern side of the Tibetan Plateau, with maximum water vapor flux exceeding 12 $g \cdot cm^{-1} \cdot hPa^{-1}$, transporting water vapor via the southwest path to the rainstorm area. This water vapor transport path is similar to the "southwest-south" path in Zhang Junlan et al.'s study, but with greater intensity.

At 850 hPa, a strong low-level easterly jet existed north of the rainstorm area, carrying water vapor via the easterly path to the rainstorm area with maximum flux exceeding 12 $g \cdot cm^{-1} \cdot hPa^{-1}$. This is consistent with Liu Jing et al.'s research, though the water vapor flux intensity in this rainstorm was greater. Such upper- and lower-level water vapor transport paths created strong water vapor coupling over the rainstorm area, favoring rainstorm development and intensification. At 20:00 on June 15, the mid-latitude trough continued to extend southward to near 40°N, with the subtropical high extending westward and northward. The southwest flow ahead of the trough converged with the southeasterly flow on the southwestern side of the subtropical high, transporting water vapor via the southwest path to the rainstorm area with maximum flux of 8 $g \cdot cm^{-1} \cdot hPa^{-1}$. Due to the northward shift of the subtropical high, water vapor from its northern side was transported to the north of the rainstorm area, making the southwest path the main water vapor source at this time. At 850 hPa, the low-level easterly jet north of the rainstorm area strengthened, continuously transporting water vapor via the easterly path to the rainstorm area (Figure 4), providing sufficient water vapor supply.

For the rainstorm's physical processes, strong water vapor transport must be accompanied by water vapor convergence. Figure 5 shows the latitudinal-vertical cross-section of water vapor flux divergence at the three rainstorm stations. All three stations exhibited water vapor flux convergence with intensity reaching -12×10^{-6} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot h^{-1}$. This is because the stations are all located on the northern slope of the Kunlun Mountains, where the low-level easterly jet transports water vapor to the rainstorm area, forming strong convergence due to topographic blocking and causing water vapor accumulation, providing favorable moisture conditions for rainstorm occurrence and development.

2.4 Local PWV Variation Characteristics

Using GPS/Met data from Hotan, Pishan, and Yutian stations—the three stations nearest to the precipitation centers—we further analyzed temporal evolution characteristics of PWV. Since these three stations are closest to the centers, we used their data to analyze PWV variation characteristics for the three heavy precipitation centers with strongest cumulative precipitation, with results shown in Figure 6. Under the background of large-scale water vapor transport, PWV variation characteristics were similar across the three stations, all showing rapid moistening processes. For the two stations experiencing short-duration heavy precipitation, we can see from Figure 6 that before heavy precipitation at Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County, as the Central Asian low vortex developed southwest of Lake Balkhash, the mid-latitude trough ahead of the low vortex extended southward to near 40°N while the subtropical high extended westward and northward. The southwest flow ahead of the trough converged with the southerly flow on the western side of the subtropical high over the Tibetan Plateau and transported water vapor to the rainstorm area, causing PWV to increase significantly from 16.75 mm at 00:00 on June 15 to a maximum of 30.03 mm at 16:00. Liu Jing et al. calculated the climate mean PWV in June in the Hotan area as 9.65 mm, making the peak value 3.1 times the climate mean. PWV gradually decreased after 00:00 on June 16 as the precipitation process ended.

Due to strengthening of the mid-latitude trough ahead of the southwest flow continuously transporting water vapor to the station, the Langan Township Kunlun Canal Head Station also showed significant moistening before heavy precipitation, increasing from 10.75 mm at 19:00 on June 15 to 19.91 mm at 22:00, with the peak being 2.2 times the climate mean of 9.16 mm. Notably, although this station's PWV was significantly lower than other stations, its PWV showed a large increase in a short time before the heavy precipitation event, meaning rapid moistening occurred over the station, promoting short-duration heavy precipitation. For the continuous precipitation at Buqiong Village Station, results show that at the initial precipitation stage (23:00 on June 14), water vapor was transported only by the mid-latitude trough ahead of the southwest flow.

As the mid-latitude trough continuously extended southward and strengthened, the southwest flow ahead of the trough enhanced and continuously gathered water vapor with the southerly flow on the western side of the subtropical high (Figure 4), causing PWV to increase significantly from 14.96 mm at 23:00 on June 14 to 28.01 mm at 22:00 on June 15, with the peak being 2.1 times the climate mean of 13.05 mm. After 23:00 on June 15, PWV slowly decreased but remained above 20 mm, with the mid-latitude trough ahead of the southwest flow continuously transporting water vapor over the station, while the low-level easterly jet and topographic effects accumulated water vapor, which may be the key to the long duration of precipitation at this station.

Comprehensive analysis shows that the three stations with maximum cumulative precipitation all had favorable moisture conditions, with continuous water vapor transport aloft and strong water vapor flux convergence centers, causing significant moistening processes at the stations before short-duration heavy precipitation and during continuous precipitation. Additionally, comparison of water vapor transport paths shows that Buqiong Village Station and Langan Township Kunlun Canal Head Station mainly received water vapor via the southwest path in the middle troposphere (500 hPa), while Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County received water vapor mainly via the southwest-turning-south path. The lower layer (850 hPa) was dominated by water vapor transport carried by low-level easterly jets. The coupling of water vapor transport paths between middle and lower layers promoted the development and intensification of this extreme rainstorm.

2.5 Mesoscale Convective System Characteristics

Stationary satellite data have high temporal-spatial resolution, especially FY-2H TBB data, which can observe not only large-scale cloud distribution but also the entire evolution process of mesoscale cloud systems from generation and development to maturity and dissipation. This study uses 30-minute interval FY-2H TBB data with 0.1°$×$0.1° horizontal resolution to analyze the generation, development, and movement characteristics of mesoscale convective cloud clusters during this rainstorm process, focusing on the three stations with maximum cumulative precipitation (Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County, Buqiong Village Station, and Langan Township Kunlun Canal Head Station). Based on Xinjiang's specific geographic environment, the criteria from Zheng Yongguang et al. are referenced for mesoscale convective cloud cluster identification.

Figure 7 shows the 30-minute evolution of TBB near the rainstorm area from 19:30 to 23:30 on June 15. Under the large-scale circulation background of "two highs sandwiching one low" (Figure 3), a mesoscale convective cloud cluster with center intensity of -40°C generated at 19:30 south of the rainstorm area. As the Western Pacific subtropical high continuously extended westward and northward, the cloud cluster north of the station also developed and moved northward with the southwest steering flow ahead of the trough. At 20:30, the mesoscale convective cloud cluster split into two meso-β scale convective cloud clusters arranged in a northwest-southeast direction distributed east of Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County, maintaining in the next time period with center intensity of -40°C. Affected by this, Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County experienced short-duration heavy precipitation with maximum hourly intensity of 29.4 mm. The station was located at the maximum gradient of the TBB, consistent with previous research. With the dissipation of the mesoscale convective cloud cluster at 23:00, another mesoscale convective cloud cluster generated to its south with center intensity of -36°C, continuously moving northward, increasing in scale, and slowly moving northwestward to over Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County at 23:30 (Figure 7). The short-duration heavy precipitation at this station was mainly caused by the train-effect-type and merging-strengthening-type mesoscale convective cloud clusters continuously generating, developing, and moving over the station, with the station located at the maximum TBB gradient of the convective cloud clusters.

Figure 8 shows the 30-minute TBB evolution from 00:00 to 04:00 on June 16. At 00:00, a mesoscale convective cloud band arranged southwest-northeast existed over Buqiong Village Station, formed by the merger and development of convective cloud clusters from the previous time period, with convective cloud clusters within the band having center intensity of -40°C. Subsequently, the mesoscale convective cloud band continuously affected Buqiong Village Station, with new meso-β and meso-α scale convective cloud clusters continuously generating within the band, their intensity and scale continuously increasing and maintaining over the rainstorm area (Figure 8). Under the influence of this convective cloud band and strong mesoscale convective cloud clusters, all three stations produced strong precipitation. Notably, Langan Township Kunlun Canal Head Station experienced short-duration heavy precipitation from 03:00 to 04:00, when the station was located at the maximum TBB gradient of the convective cloud band.

Figure 9 shows the 30-minute TBB evolution from 04:30 to 08:30 on June 16. During this period, the convective cloud band first maintained over the rainstorm area, then continuously moved northward to the north of the rainstorm area. The mesoscale convective cloud clusters within the band continuously affected the rainstorm area stations, then the convective cloud band continuously split and moved out of the rainstorm area. At 02:30, the convective cloud band merged with the convective cloud band to its west, forming a vortex-like convective cloud band covering the rainstorm area (Figure 9). At this time, the Central Asian low vortex formed and maintained over western southern Xinjiang, with the vortex-like convective cloud band forming in the peripheral steering flow of the Central Asian low vortex. Subsequently, new meso-β and meso-α scale convective cloud clusters continuously generated within the convective cloud band, with their intensity and scale continuously increasing and maintaining over the rainstorm area (Figure 9). Under the influence of this convective cloud band and strong mesoscale convective cloud clusters, all three stations produced strong precipitation, though intensity decreased. Finally, as convective cloud clusters continuously moved northward out of the rainstorm area, precipitation processes at Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County and Langan Township Kunlun Canal Head Station tended to end (figure omitted). Due to Buqiong Village Station's continuous influence by the periphery of the convective cloud band, persistent precipitation occurred but with weaker intensity.

In summary, the rainstorm processes at the three stations with maximum cumulative precipitation in Hotan Prefecture on the northern slope of the Kunlun Mountains were caused by continuous generation and development of mesoscale convective cloud clusters near the rainstorm area that moved to and intensified over the rainstorm area, directly triggering the extreme rainstorm. The mesoscale convective cloud clusters affecting this rainstorm process were mainly meso-β and meso-α scale clusters, as well as mesoscale convective cloud bands with banded and vortex-like distributions. The short-duration heavy precipitation at Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County was mainly caused by northwest-southeast oriented train-effect-type meso-β convective cloud clusters continuously generating, developing, and moving over the station, with the station located at the maximum TBB gradient. Buqiong Village Station's continuous precipitation resulted from persistent influence by mesoscale convective cloud clusters and continuous coverage by vortex-like mesoscale convective cloud bands. The vortex-like convective cloud band was the key system causing short-duration heavy precipitation at Langan Township Kunlun Canal Head Station, with the station located at the maximum TBB gradient for 1 hour. Compared with previous studies, the mesoscale convective cloud clusters in this extreme rainstorm process had shorter duration, with TBB higher than statistical values, indicating that convective extension height in this extreme rainstorm process was not particularly high.

3 Conclusions

Based on high temporal-spatial resolution meteorological observations, GPS/Met PWV data, Fengyun satellite data, and ERA5 reanalysis data, this study analyzed the mesoscale characteristics of the extreme rainstorm process on the northern slope of the Kunlun Mountains from June 14–17, 2021. The main conclusions are as follows:

(1) This extreme rainstorm process featured large cumulative precipitation, numerous rainstorm stations, strong locality, and extreme intensity. The maximum rainfall center was at Shangpulu Debris Flow Frequent Area Station No. 1 in Luopu County (121.6 mm), followed by Buqiong Village Station (107.8 mm) and Langan Township Kunlun Canal Head Station (102.1 mm). Shangpulu Debris Flow Frequent Area Station No. 1 and Langan Township Kunlun Canal Head Station experienced short-duration heavy precipitation, while Buqiong Village Station had lower precipitation

intensity but longer duration.

(2) This extreme rainstorm process occurred under the favorable circulation background of "two ridges and one trough," with a dual-body South Asian high in the upper level and the formation and development of a Central Asian low vortex as the key influencing system. The rainstorm area was located to the right of the 200 hPa southwest jet entrance, which, combined with low-level jets, created strong upper-level divergence and lower-level convergence that promoted vertical atmospheric motion development, providing favorable dynamic conditions for rainstorm triggering. The 500 hPa southerly flow, 700 hPa shear line, and 850 hPa easterly flow cooperated to provide favorable dynamic configuration and facilitated water vapor transport and accumulation in the rainstorm area, promoting the occurrence and development of this extreme rainstorm.

(3) Water vapor flux transport in the middle and lower layers, water vapor flux divergence, and local PWV changes at the three heavy precipitation centers showed that due to the influence of mid-latitude troughs and plateau systems, continuous water vapor transport from the southwest ahead of the trough and from the south on the western side of the plateau existed before rainstorm occurrence, with strong water vapor flux convergence centers near the stations, causing PWV to show significant moistening in a short time before short-duration heavy precipitation and during continuous precipitation. Further comparison revealed that PWV at Shangpulu Debris Flow Frequent Area Station No. 1 and Langan Township Kunlun Canal Head Station, which experienced short-duration heavy precipitation, significantly decreased after heavy precipitation, accompanying the end of precipitation, while PWV at Buqiong Village Station, which experienced continuous precipitation, showed smaller decrease after precipitation, indicating continuous water vapor accumulation that resulted in the longest precipitation duration at this station. Therefore, PWV shows good indicative significance for monitoring extreme rainstorms. Comparison of water vapor transport paths revealed that Buqiong Village Station and Langan Township Kunlun Canal Head Station mainly received water vapor via the southwest path in the middle troposphere (500 hPa), while Shangpulu Debris Flow Frequent Area Station No. 1 received water vapor mainly via the southwest-turning-south path. The lower layer (850 hPa) was dominated by water vapor transport carried by low-level easterly jets. The coupling of water vapor transport paths between middle and lower layers promoted the development and intensification of this extreme rainstorm.

(4) Analysis of convective cloud cluster activity characteristics during this rainstorm process using FY-2H 30-minute TBB data showed that mesoscale convective cloud clusters continuously generated and developed near the rainstorm area and intensified after moving to the rainstorm area, serving as the direct influencing system triggering the extreme

rainstorm. This rainstorm process mainly involved meso-β and meso-α scale convective cloud clusters, as well as mesoscale convective cloud bands with banded and vortex-like distributions. The short-duration heavy precipitation at Shangpulu Debris Flow Frequent Area Station No. 1 was mainly caused by northwest-southeast oriented train-effect-type meso-β convective cloud clusters continuously generating, developing, and moving over the station, with the station located at the maximum TBB gradient. Buqiong Village Station's continuous precipitation resulted from persistent influence by mesoscale convective cloud clusters and continuous coverage by vortex-like mesoscale convective cloud bands. The vortex-like convective cloud band was the key system causing short-duration heavy precipitation at Langan Township Kunlun Canal Head Station, with the station located at the maximum TBB gradient for 1 hour. Compared with previous studies, the mesoscale convective cloud clusters in this extreme rainstorm process had shorter duration, with TBB higher than statistical values.

This paper only analyzed mesoscale characteristics of this extreme rainstorm process based on observational data, Fengyun satellite data, and reanalysis data. Future work will use more satellite products and numerical simulations to deeply investigate mesoscale system characteristics triggering rainstorms and mesoscale convective triggering mechanisms, thereby improving precipitation monitoring and forecasting capabilities in the northern Kunlun Mountains slope region and providing references for early warning.

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