Characteristics and Differences of Heavy Rainfall in the Western and Middle Sections of the Northern Slope of the Kunlun Mountains: Postprint

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Abstract

Using precipitation data from national meteorological stations and reanalysis data on the northern slope of the Kunlun Mountains from 1961 to 2023, this study reveals the characteristics and differences of heavy rain between the western and middle sections of the northern slope of the Kunlun Mountains. The results show that: (1) From 1961 to 2023, both the number of heavy rain days and heavy rain amount in the western and middle sections of the northern slope of the Kunlun Mountains exhibited increasing trends, with more significant increases in the western section; the cumulative number of heavy rain days and cumulative heavy rain amount in the western section were both greater than those in the middle section; however, the difference in extreme rainfall amounts between the two sections was not significant; the heavy rain amount in the western section during the warm-wet phase was greater than that during the warm-dry phase, while the opposite was true for the middle section, indicating different responses to climate transition. (2) The spatial distributions of both the number of heavy rain days and heavy rain amount in the western section of the northern slope of the Kunlun Mountains showed an "east-more-west-less" pattern, while those in the middle section displayed a "middle-more-sides-less" pattern; the spatial distributions of average heavy rain amount and cumulative heavy rain amount were consistent in the western section but opposite in the middle section. (3) From 2010 to 2023, over 90% of national stations on the northern slope of the Kunlun Mountains experienced short-duration heavy precipitation events, a proportion higher than the average for southern Xinjiang; the western section as a whole (middle section) was dominated by non-short-duration (short-duration) heavy precipitation events. Heavy rain events on the northern slope of the Kunlun Mountains showed poor persistence and were predominantly nocturnal, with similar average precipitation durations between the western and middle sections. (4) The typical configuration of main weather systems causing heavy rain in both the western and middle sections of the northern

slope of the Kunlun Mountains was identical, which increases the difficulty of fine-scale location forecasting for heavy rain on the northern slope of the Kunlun Mountains. The research results can deepen understanding of the uniqueness of heavy rain in arid regions and provide references for improving heavy rain disaster prevention capabilities on the northern slope of the Kunlun Mountains.

Full Text

Characteristics and Differences in Heavy Rainfall in the Western and Central Sections of the Northern Slope of the Kunlun Mountains

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Abstract

This study utilizes precipitation data from national meteorological stations and reanalysis data from 1961 to 2023 to reveal the characteristics and differences of heavy rainfall in the western and central sections of the northern slope of the Kunlun Mountains. The results show that: (1) From 1961 to 2023, both the number of heavy rainfall days and the total heavy rainfall amount exhibited increasing trends in both sections, with the western section showing a more significant increase. The cumulative number of heavy rainfall days and cumulative rainfall amount were greater in the western section than in the central section, though the difference in extreme rainfall values was not substantial. Heavy rainfall in the western section was more frequent during the warm-humid phase compared to the warm-dry phase, while the central section showed the opposite pattern, indicating different responses to climate transition. (2) The spatial distribution of heavy rainfall days and amounts in the western section displayed an "east-more-west-less" pattern, whereas the central section showed a "middle-more-sides-less" pattern. The spatial distribution of average heavy rainfall was consistent with cumulative heavy rainfall in the western section but opposite in the central section. (3) Over 90% of stations on the northern slope experienced short-duration heavy rainfall events, a proportion higher than the southern Xinjiang average. The western section was dominated by non-short-duration heavy rainfall events, while the central section was dominated by short-duration events. Heavy rainfall events on the northern slope showed poor persistence and predominantly nocturnal occurrence, with similar average precipitation durations between the two sections. (4) The typical configuration of main weather systems causing heavy rainfall was identical in both sections, which increases the difficulty of precise location forecasting for heavy rainfall on the northern slope of the Kunlun Mountains. These findings deepen our

understanding of the unique characteristics of heavy rainfall in arid regions and provide references for improving disaster prevention capabilities.

Keywords: heavy rainfall; climatic characteristics; diurnal variation; weather systems; northern slope of the Kunlun Mountains

1. Introduction

The Kunlun Mountains form the main western mountain system in China, spanning a large east-west extent with a total length of approximately 2,500 km, and are geographically divided into West Kunlun, Central Kunlun, and East Kunlun [1]. The northern slope of the Kunlun Mountains serves as a crucial corridor for constructing the core area of the Silk Road Economic Belt and is located in the inland arid region of Northwest China, where water resources are a key factor affecting regional economic and social development [2]. The annual precipitation on the northern slope of the Kunlun Mountains shows large interannual variability [3] and uneven intra-annual distribution, with precipitation concentrated mainly in the warm season (May-September), and spatially characterized by more precipitation in the south and less in the north [4]. In recent years, with global warming and the climate transition in Xinjiang toward warm-humid conditions [5,6], heavy rainfall events have occurred frequently on the northern slope of the Kunlun Mountains [7]. Although the total precipitation from a single heavy rainfall event is far less than that in the monsoon region of eastern China, its relative intensity can be comparable to or even exceed that of monsoon region heavy rainfall [8].

Heavy rainfall on the northern slope of the Kunlun Mountains is characterized by strong suddenness, short duration [9], and extreme intensity. Currently, operational forecasting experiences numerous false alarms and missed predictions for heavy rainfall in this region, resulting in inadequate disaster prevention capacity. Previous studies have often analyzed the northern slope of the Kunlun Mountains together with southern Xinjiang (hereinafter referred to as "Southern Xinjiang") as a whole, paying insufficient attention to the particularities of heavy rainfall on the northern slope of the Kunlun Mountains [10]. Existing research on heavy rainfall in this region is relatively limited and primarily focuses on individual case analyses [11,12].

The formation conditions for heavy rainfall in arid regions are more stringent than in monsoon regions, requiring close coordination between large-scale circulation backgrounds and multi-scale weather systems [13]. Studies have shown that the South Asian High, Central Asian low vortex, and Tarim easterly low-level jet are important weather systems causing heavy rainfall in Southern Xinjiang [14,15]. Heavy rainfall in Southern Xinjiang is often triggered by meso- and small-scale weather systems such as surface convergence lines and mesoscale vortices. Moisture conditions are crucial for heavy rainfall in arid regions, with different regions in Southern Xinjiang having distinct moisture sources and transport pathways [16]. Water vapor from high-latitude Siberian regions and low-latitude sources including the Bay of Bengal, Arabian Sea, and tropical Indian Ocean are all associated with heavy rainfall in Southern Xinjiang [17]. The terrain surrounded by mountains on three sides in Southern Xinjiang creates special vortex source and sink effects, which, combined with the Tarim easterly low-level jet, provide favorable dynamic and moisture conditions for heavy rainfall.

Research indicates that significant changes have occurred in the spatiotemporal characteristics and influencing systems of heavy rainfall in Southern Xinjiang over the past 60 years [18]. How has heavy rainfall in different regions of the northern slope of the Kunlun Mountains changed over long time scales? Are these change characteristics consistent with the overall changes in Southern Xinjiang? These questions remain unclear. This paper uses precipitation data from national meteorological stations and reanalysis data to focus on discussing the changing characteristics of heavy rainfall in different regions of the northern slope of the Kunlun Mountains, aiming to provide references for improving disaster risk prevention capabilities against heavy rainfall in this region.

2. Data and Methods

This study uses daily precipitation data from 1961 to 2023 and hourly precipitation data from 2010 to 2023 at national meteorological stations on the northern slope of the Kunlun Mountains (Fig. 1 [Figure 1: see original paper]) to analyze the climatic characteristics and differences of heavy rainfall in the western section (hereinafter "western section") and central section (hereinafter "central section") of the northern slope of the Kunlun Mountains.

Xinjiang, located in an arid region, has different criteria for heavy rainfall and short-duration heavy precipitation compared to national standards. In Xinjiang, heavy rainfall refers to daily precipitation \$ \$12.0 mm, and short-duration heavy precipitation refers to precipitation \$ \$10.0 mm per hour [19,20]. If a heavy rainfall process simultaneously includes a short-duration heavy precipitation event, it is defined as a short-duration heavy rainfall event; otherwise, it is defined as a non-short-duration heavy rainfall event. In this paper, "daytime rainfall" refers to precipitation occurring between 08:00-20:00 (Beijing Time), and "nocturnal rainfall" refers to precipitation occurring between 20:00-08:00.

2.1. Temporal Variation Characteristics

2.1.1. Heavy Rainfall Days Figure 2 [Figure 2: see original paper] shows that from 1961 to 2023, the number of heavy rainfall days in both the western and central sections of the northern slope of the Kunlun Mountains exhibited increasing trends. The western section increased at an average rate of 0.1 days per decade, passing the significance test at the α=0.05 level, while the central section showed a weaker increasing trend that failed the significance test (Fig. 2a [Figure 2: see original paper]). Heavy rainfall in the western section occurred mainly in July, accounting for 48.8% of the total, followed by June

(18.6%). The distribution of heavy rainfall days across warm-season months in the central section differed significantly from the western section, with the highest proportion occurring in June and August, each accounting for 28.6% and 20.0%, respectively.

The number of heavy rainfall days in the western and central sections also showed substantial differences at the interdecadal scale (Fig. 2b [Figure 2: see original paper]). The western section had the fewest heavy rainfall days in the 1960s, while the central section had the fewest in the 1970s. Overall, the proportion of heavy rainfall days in different decades showed opposite variation characteristics between the two sections. In summary, heavy rainfall days on the northern slope of the Kunlun Mountains exhibit obvious regional differences, with the western and central sections showing different temporal variation characteristics that are not synchronized.

2.1.2. Heavy Rainfall Amount Similar to heavy rainfall days, both the western and central sections showed increasing trends in heavy rainfall amount from 1961 to 2023 (Fig. 3 [Figure 3: see original paper]). The western section increased at an average rate of 9.8 mm per decade, passing the significance test at α=0.05, while the central section increased at 4.0 mm per decade but failed the significance test (Fig. 3a [Figure 3: see original paper]). From 1961 to 2023, the cumulative heavy rainfall amount was 2,221.0 mm in the western section and 1,478.5 mm in the central section, with annual averages of 34.7 mm and 23.1 mm, respectively.

Consistent with heavy rainfall days, the western section' s heavy rainfall amount peaked in July, accounting for 53.4% of the total cumulative amount. The central section' s monthly distribution of heavy rainfall amount differed from that of heavy rainfall days: although June had the highest proportion of heavy rainfall days, August had the largest proportion of cumulative heavy rainfall amount (36.2%). At the interdecadal scale (Fig. 3b [Figure 3: see original paper]), the proportions of heavy rainfall amount in the western and central sections showed opposite variation characteristics in the 1960s-1990s, but both exhibited consistent increasing trends after entering the 2000s.

Research shows that Xinjiang' s climate transitioned from warm-dry to warm-humid beginning in the late 1980s, with precipitation showing obvious phased growth characteristics [6]. Figure 3b [Figure 3: see original paper] reveals that heavy rainfall in the western section increased significantly after 1987, with 73.2% of the total heavy rainfall amount occurring during the warm-humid phase. In contrast, the central section showed different characteristics: 53.3% of the total heavy rainfall amount occurred during the warm-dry phase (1960s-1980s), while 46.7% occurred during the warm-humid phase (1987-2023). This indicates that different regions of the northern slope of the Kunlun Mountains respond differently to climate transition.

2.2. Spatial Characteristics

The spatial distribution of cumulative heavy rainfall days differs significantly between the western and central sections. The western section shows an overall "east-more-west-less" pattern, with high-value areas near 77°E, while the central section displays a "middle-more-sides-less" pattern, with cumulative heavy rainfall days gradually decreasing from the middle to both east and west sides (Fig. 4a [Figure 4: see original paper]). The spatial distribution characteristics of cumulative heavy rainfall amount are similar to those of cumulative heavy rainfall days (Fig. 4b [Figure 4: see original paper]).

The spatial distribution of average heavy rainfall amount in the western section is similar to that of cumulative heavy rainfall amount, but in the central section, the two distributions are opposite—that is, the average heavy rainfall amount shows a "middle-less-sides-more" pattern (Fig. 4c [Figure 4: see original paper]). Comparison of Figs. 4b and 4c reveals that large cumulative heavy rainfall amounts on the northern slope of the Kunlun Mountains are mainly caused by numerous heavy rainfall days, though at some stations, small cumulative amounts coexist with large average amounts. For example, Moyu Station in the central section has the smallest cumulative heavy rainfall amount in the study area but the largest average heavy rainfall amount, having experienced only one heavy rainfall event in the past 63 years, during which precipitation reached 59.6 mm—approximately 1.3 times its annual average precipitation.

The spatial distribution characteristics of heavy rainfall in the central section also reflect the particularity of heavy rainfall in arid regions: although annual heavy rainfall frequency and amount are far lower than in eastern China' s monsoon region, the relative intensity can be greater and even exceed monsoon region heavy rainfall [8]. The daily maximum heavy rainfall amount in the western section gradually decreases from east to west, with Pishan Station recording the maximum (74.6 mm) and Kashgar Station the minimum (39.9 mm). The spatial distribution of daily maximum heavy rainfall amount in the central section is similar to that of average heavy rainfall amount, with Luopu Station recording the maximum (74.1 mm) and Cele Station the minimum (37.9 mm). Although the central section has significantly fewer cumulative heavy rainfall days than the western section, the difference in extreme rainfall amounts between the two sections is small, indicating that while heavy rainfall occurs less frequently in the central section, the extreme rainfall intensity is comparable to that in the western section.

2.3. Short-Duration Heavy Precipitation Events

Heavy rainfall processes in arid regions are often accompanied by short-duration heavy precipitation events [21]. Figure 5 [Figure 5: see original paper] shows that from 2010 to 2023, all stations except Kashgar experienced short-duration heavy precipitation events during heavy rainfall days, with proportions exceeding 75.3%—much higher than the average for other regions in Southern Xinjiang.

The spatial distribution of short-duration heavy rainfall days in both sections is similar to their respective cumulative heavy rainfall days, with stations having more heavy rainfall days also experiencing more short-duration heavy rainfall days.

The proportion of short-duration heavy rainfall days in the western section is generally lower than in the central section, with regional average proportions of 45.2% and 54.8%, respectively. The spatial distribution of short-duration heavy rainfall amount also shows obvious regional differences, decreasing significantly from east to west in the western section, with Yecheng Station' s cumulative amount being about 2.3 times that of Aktao Station. The differences in short-duration heavy rainfall amount among stations in the central section are smaller than in the western section, with Luopu Station recording the maximum and Yutian Station the minimum, differing by approximately 1.4 times. The proportion of short-duration heavy rainfall amount in the central section is also higher than in the western section, especially at stations on both sides of the central section with fewer cumulative heavy rainfall days, where the proportion of heavy rainfall events accompanied by short-duration heavy precipitation reaches 61.9%.

In summary, the western section is dominated by non-short-duration heavy rainfall events, while the central section is dominated by short-duration heavy rainfall events. Water vapor is a crucial condition for heavy rainfall formation. Since moisture conditions in the western section are better than in the central section [22], the western section has more heavy rainfall days. In addition to short-duration heavy rainfall events occurring in convective weather, stable long-duration precipitation can also produce heavy rainfall in the western section. In contrast, due to perennial water vapor scarcity in the central section [23], conditions for heavy rainfall formation are more stringent, requiring strong convective processes with intense upward motion and rapid moisture convergence by meso- and small-scale systems to produce heavy rainfall, making short-duration heavy precipitation more likely to occur during heavy rainfall events.

2.4. Diurnal Variation

Significant regional differences exist in the diurnal variation of precipitation [24], but previous studies often treated Southern Xinjiang as a whole when examining diurnal variations of different precipitation types [25], thus failing to reveal regional differences. Figure 6 [Figure 6: see original paper] shows that from 2010 to 2023, cumulative precipitation from short-duration heavy rainfall events in the western section was significantly greater than from non-short-duration events, with the two types showing opposite diurnal distributions. Short-duration heavy rainfall peaked during 15:00-05:00, with maximum cumulative precipitation at 18:00-22:00, while non-short-duration heavy rainfall occurred mainly during 08:00-14:00.

Unlike cumulative precipitation, the frequency of non-short-duration heavy rainfall events in the western section was higher than that of short-duration events. The frequency peak for non-short-duration events occurred during 09:00-13:00, while for short-duration events it was during 02:00-04:00, with a low-frequency period during 12:00-17:00. Heavy rainfall in the western section overall showed more nocturnal than daytime occurrence, with short-duration heavy rainfall showing similar day-night distribution to total heavy rainfall, while non-short-duration heavy rainfall showed the opposite pattern with more daytime than nocturnal rainfall.

The diurnal variation characteristics of cumulative precipitation in the central section differed from those in the western section, with both heavy rainfall types showing consistent bimodal distributions. The diurnal variation of short-duration heavy rainfall intensity in the western section was greater than non-short-duration events during 13:00-21:00 but smaller during other periods. In the central section, the diurnal variation of short-duration heavy rainfall intensity was opposite to that in the western section, being greater during 08:00-14:00. In summary, the diurnal variation characteristics of different heavy rainfall types differ between the western and central sections, and the diurnal variation characteristics of the same heavy rainfall type also differ significantly between these two regions.

Table 1 shows that heavy rainfall in the western section overall had more nocturnal than daytime precipitation, with short-duration heavy rainfall showing similar day-night distribution to total heavy rainfall, while non-short-duration heavy rainfall showed the opposite pattern. The day-night distribution characteristics of different heavy rainfall types in the central section were consistent, all showing more nocturnal than daytime precipitation. Thus, heavy rainfall on the northern slope of the Kunlun Mountains overall shows more nocturnal than daytime occurrence, but the day-night distribution of non-short-duration heavy rainfall differs significantly between the western and central sections. Previous studies treating Southern Xinjiang as a whole concluded that nocturnal rainfall predominates, mainly related to the nocturnal strengthening of low-level jets [26], but the regional differences in day-night distribution of non-short-duration heavy rainfall on the northern slope of the Kunlun Mountains require further investigation.

2.5. Duration

From 2010 to 2023, only three stations—Kashgar and Yecheng in the western section and Cele in the central section—experienced consecutive heavy rainfall processes, while all other stations had only single-day heavy rainfall processes. Thus, due to water vapor scarcity in arid regions, the continuous moisture supply capacity during heavy rainfall processes is poor, making consecutive multi-day heavy rainfall events rare in the same region.

Table 2 shows that the average precipitation duration for heavy rainfall in the western section was 15.4 hours, with short-duration heavy rainfall averaging

7.9 hours (about 43% of non-short-duration events' 18.1 hours). The average precipitation duration for heavy rainfall in the central section was similar to that in the western section at 13.5 hours, but with different composition: short-duration heavy rainfall averaged 11.6 hours (about 75% of non-short-duration events' 15.4 hours). Thus, while the overall average precipitation duration is similar between the two sections, short-duration heavy rainfall in the western section lasts about 3.7 hours shorter than in the central section, while non-short-duration heavy rainfall lasts about 2.7 hours longer.

2.6. Main Influencing Systems

Heavy rainfall is the product of multi-scale weather systems working together [27]. Studies show that the South Asian High at 100 hPa, Central Asian low vortex (trough) at 500 hPa, and Tarim easterly low-level jet at 850 hPa are important large-scale weather systems causing heavy rainfall in Southern Xinjiang [14,16]. When the South Asian High is in the "Qinghai-Tibet High" pattern, the subtropical westerly trough controlling Southern Xinjiang deepens southward, enhancing upper-level divergence over the heavy rainfall area. The southwestern airflow ahead of the Central Asian low trough at 500 hPa facilitates water vapor transport from the southern branch to the heavy rainfall area, while positive vorticity advection ahead of the trough provides favorable large-scale conditions for heavy rainfall formation. The Tarim easterly low-level jet at 850 hPa causes low-level airflow convergence and upward motion, and the vertical motion induced by the low-level jet, combined with the three-sided mountainous terrain of Southern Xinjiang, creates a coupling between low-level convergence and upper-level divergence, further promoting the development of vertical upward motion throughout the atmospheric column. Meanwhile, the Tarim easterly low-level jet continuously transports and converges low-level moisture into the heavy rainfall area, providing sustained moisture conditions for heavy rainfall.

Table 3 shows that in heavy rainfall events in the western section, the South Asian High is dominated by the "Qinghai-Tibet High" pattern (57.1%), followed by the "double-body type" (31.0%) and "Iranian High" pattern (11.9%). At 500 hPa, the proportion of Central Asian low troughs (54.8%) is higher than that of Central Asian low vortices (45.2%). At 850 hPa, the proportion with Tarim easterly low-level jet (61.9%) is significantly higher than without it (38.1%). Comparing these proportions between the western and central sections reveals that the main weather systems at different levels have identical typical configurations.

Since heavy rainfall in both the western and central sections of the northern slope of the Kunlun Mountains occurs under consistent typical configurations of main weather systems at high, middle, and low levels (South Asian High dominated by "Qinghai-Tibet High" pattern; 500 hPa dominated by Central Asian low trough; 850 hPa mostly accompanied by Tarim easterly low-level jet), it is difficult to determine the precise location of heavy rainfall based on large-scale circulation background alone, representing a major challenge for heavy rainfall location forecasting on the northern slope of the Kunlun Mountains. Studies show that heavy rainfall is directly produced by meso- and small-scale weather systems under favorable synoptic backgrounds [28]. Therefore, how to identify the development and evolution of meso- and small-scale weather systems under the same synoptic background is key to accurately forecasting heavy rainfall location on the northern slope of the Kunlun Mountains—a question to be addressed in future research.

3. Conclusions and Discussion

Based on analysis of heavy rainfall climatic characteristics and circulation differences in the western and central sections of the northern slope of the Kunlun Mountains from 1961 to 2023, the main conclusions are:

(1) The western section of the northern slope of the Kunlun Mountains has more heavy rainfall days and greater amounts than the central section. From 1961 to 2023, both sections showed increasing trends in heavy rainfall days and amounts, with the western section' s increase being more significant. Heavy rainfall days and amounts peaked in July in the western section, while the central section had maximum heavy rainfall days in June and August but maximum heavy rainfall amount in August. The proportion of heavy rainfall days in different decades showed opposite variation characteristics between the two sections. The response of heavy rainfall amounts to climate transition differed between sections, with heavy rainfall in the western section occurring mainly during the warm-humid phase, while the central section' s heavy rainfall occurred mainly during the warm-dry phase.

(2) Spatial distribution differences in heavy rainfall days and amounts are substantial between different regions of the northern slope of the Kunlun Mountains. Cumulative heavy rainfall days and amounts show an "east-more-west-less" pattern in the western section and a "middle-more-sides-less" pattern in the central section. The spatial distribution of average heavy rainfall amount is consistent with cumulative heavy rainfall amount in the western section but opposite in the central section. Over 90% of stations on the northern slope have experienced short-duration heavy rainfall events, a proportion higher than the Southern Xinjiang average. The western section is dominated by non-short-duration heavy rainfall events, while the central section is dominated by short-duration events.

(3) Heavy rainfall persistence on the northern slope of the Kunlun Mountains is relatively poor, with consecutive heavy rainfall processes being rare in the same region. The average precipitation duration of heavy rainfall is similar between the western and central sections, though short-duration heavy rainfall in the western section lasts about 4 hours shorter than in the central section, while non-short-duration heavy rainfall lasts about 3 hours longer. Heavy rainfall overall shows more nocturnal than daytime

occurrence, but the day-night distribution of non-short-duration heavy rainfall differs between the western and central sections.

(4) When heavy rainfall occurs in both the western and central sections of the northern slope of the Kunlun Mountains, the typical configuration of main weather systems at high, middle, and low levels is identical (South Asian High dominated by "Qinghai-Tibet High" pattern; 500 hPa dominated by Central Asian low trough; 850 hPa mostly accompanied by Tarim easterly low-level jet), making precise location forecasting of heavy rainfall difficult.

Precipitation on the northern slope of the Kunlun Mountains is one of the main water resources in Southern Xinjiang [29], and optimizing the development and utilization of precipitation resources is crucial for sustainable socioeconomic development in this region [30]. Previously, meteorological observation data in the Kunlun Mountains were scarce, limiting in-depth research on precipitation characteristics. In recent years, with the construction of modern meteorological station networks, particularly the successful deployment of automatic weather stations above 5,000 m elevation on the northern slope of the Kunlun Mountains in 2022, obtaining high spatiotemporal resolution precipitation data has become possible. Future work will utilize these data to analyze the detailed characteristics of precipitation on the northern slope of the Kunlun Mountains, aiming to improve understanding of heavy rainfall events and provide scientific support for disaster prevention and water resources management in this region.

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