Postprint: Diurnal Variation Characteristics of Warm-Season Precipitation in the Bayanbulak Basin, Central Tianshan Mountains

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Date: 2025-02-27T00:00:00+00:00

Abstract

As the most fundamental form of climate variation, diurnal variation of precipitation can more accurately reveal the impacts of climate change on regional water resources. To this end, based on hourly precipitation data from 18 meteorological observation stations in the Bayanbulak Basin during May–September (warm season) from 2017 to 2023, the hourly-scale precipitation patterns in this region were analyzed. The results show that: (1) The diurnal variation characteristics of precipitation amount, frequency, and intensity in the Bayanbulak Basin during the warm season are generally consistent, but exhibit differences across different time scales. At the annual scale, precipitation amount and intensity mostly increase during daytime, while precipitation frequency increases at night; at the monthly scale, all three mostly increase during the afternoon to early night period, while within a day, the period 18:00-24:00 is not only prone to precipitation but also exhibits high precipitation amounts and intensity, whereas the 07:00–10:00 period shows the opposite pattern. (2) Hourly rainfall intensity (R1) is dominated by the R1 $\leq$ 2.0 mm category, which features not only large precipitation amounts but also high frequency, followed by the 2.1 mm $\leq$ R1 $\leq$ 4.0 mm category. (3) Event precipitation amount (R) occurs most frequently during the afternoon period and makes the greatest contribution, with precipitation events of 0.1 mm $\leq$ R $\leq$ 6.0 mm (light rain) being the most frequent, but heavy to rainstorm events of R $\geq$ 12.1 mm contributing the most to total precipitation. (4) Among precipitation events of different durations, long-duration precipitation lasting more than 6 h contributes the most, but short-duration precipitation of 1–3 h tends to occur most frequently and mostly appears during the 15:00–20:00 period.

Full Text

Diurnal Variation Characteristics of Warm Season Precipitation in the Bayanbuluke Basin of the Middle Tianshan Mountains

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Abstract

Diurnal variation in precipitation represents a fundamental mode of climate change that more accurately reveals how climate variability impacts regional water resources. This study analyzes hourly precipitation patterns in the Bayanbuluke Basin, Xinjiang, during the warm season (May–September) from 2017 to 2023 using data from 18 meteorological observation stations. The results indicate that while the diurnal variation characteristics of precipitation amount, frequency, and intensity show overall consistency, they exhibit distinct differences across various time scales. On an annual scale, precipitation amount and intensity predominantly increase during daytime, whereas frequency increases at night. On a monthly scale, all three metrics show notable increases from afternoon through the first half of the night. Within a single day, the 18:00–24:00 period not only experiences more frequent precipitation but also exhibits greater amounts and intensity, while the 07:00–10:00 period shows the opposite pattern. Hourly rainfall intensity (R) peaks in the afternoon, with the greatest contributions from the 0.1 mm $\leq$ R $\leq$ 2.0 mm category, which accounts for the largest proportion of both total precipitation amount and frequency, followed by the 2.1 mm $\leq$ R $\leq$ 4.0 mm category. Among different precipitation durations, short-duration events (1-3 h) occur most frequently, primarily during 15:00–20:00, but long-duration events (R $\geq$ 12.1 mm) contribute most to total precipitation. Process precipitation (R) is dominated by light rain events (0.1 mm $\leq$ R $\leq$ 6.0 mm), yet heavy to torrential rain processes (R $\geq$ 12.1 mm) provide the largest contribution to total precipitation.

Key words: warm season; diurnal variation of precipitation; precipitation duration; Bayanbuluke Basin

1. Introduction

Diurnal variation of precipitation constitutes one of the most significant signals in global weather and climate change. Its formation is closely linked to various diurnal phenomena, but due to influences from topography, latitude, atmospheric circulation, weather systems, and land-sea distribution, different regions exhibit substantial variations in precipitation amount, temporal distribution, frequency, and extremes. These variations are intimately connected to daily life, leading the World Climate Research Programme (WCRP) in 2005 to designate precipitation diurnal variation as a scientific issue requiring special attention and focus. As a current hotspot in climate research, studying precipitation diurnal variation not only deepens understanding of the dynamic and thermodynamic processes affecting regional climate but also promotes comprehension of precipitation formation mechanisms, evaluates numerical simulation reliability, and improves weather forecasting accuracy and disaster prevention.

Numerous studies have been conducted worldwide. Kincer [7] noted in the early 20th century that precipitation peaks at stations along the southeastern U.S. coast occurred in the afternoon, while most central stations peaked at night. Yu et al. [8] found significant regional differences in the spatial distribution of summer precipitation diurnal variation across China. Xue et al. [9] and Tang et al. [10] investigated precipitation diurnal variation in the Sichuan Basin and southwestern regions, concluding that nocturnal rain was frequent in Sichuan, Chongqing, and parts of Guizhou, while Yunnan experienced more daytime precipitation. He and Zhang [11] discovered that daily precipitation peaks in the Yanshan and Taihang Mountains of North China frequently occurred at noon and afternoon, while northern grasslands peaked at night and early morning.

Located in the arid region of northwestern China, Xinjiang has relatively low total precipitation, but its unique "three mountains surrounding two basins" geographical feature has attracted numerous scholars to study local precipitation diurnal variation. Zhu et al. [12] found that hourly precipitation amount and frequency in Xinjiang during summer were greater in northern Xinjiang than in southern Xinjiang, and greater in mountainous areas than in basins. Chen et al. [13] revealed that under warm and humid conditions, Xinjiang's hourly precipitation frequency showed a pattern of more precipitation in the northwest and less in the southeast. Zheng et al. [14] found that in the Ili River Valley, mountainous areas had significantly higher precipitation amount and frequency than plains during the warm season, but lower during the cold season. Yang et al. [15] compared regional differences between winter snowfall and summer rainfall in Urumqi, finding that urban areas experienced more intense winter snowfall, while mountainous areas were more prone to intense summer rainfall. These findings demonstrate that Xinjiang's precipitation diurnal variation features differ not only regionally but also temporally, and analyzing these characteristics across different time scales can better reveal climatic patterns.

With global climate change and increasing extreme precipitation events in Xinjiang [16], hourly-scale data with higher temporal resolution can more accurately reflect precipitation variation patterns and formation mechanisms. The Bayanbuluke Basin, as a typical high-cold mountainous basin sensitive to global climate change [17], has been studied primarily using daily or longer time-scale precipitation data [18], with few analyses of hourly-scale observations. Therefore, this study analyzes diurnal precipitation characteristics across various time scales in the Bayanbuluke Basin during the warm season, aiming to provide technical support for local meteorological services and artificial weather modification operations.

2. Data and Methods

2.1 Study Area

The Bayanbuluke Basin is located in the central Tianshan Mountains, surrounded by high mountains with a flat bottom, covering an area of approximately 2.3×10^4 km^2. It features extensive marsh grasslands and lakes, along with permanent snow and glaciers. With elevations generally above 2400 m, the region exhibits a high-cold mountainous climate characterized by long winters, short summers, low evaporation, low annual temperatures, and numerous snow-covered days. Under the influence of global climate system changes, understanding the basin' s precipitation diurnal variation has become essential for improving precipitation forecasting and guiding disaster prevention and mitigation efforts.

2.2 Data Sources

This study utilizes hourly precipitation data from May to September (warm season) for 2017–2023, obtained from two national basic meteorological stations and 16 regional observation stations in the Bayanbuluke Basin, provided by the Xinjiang Meteorological Information Center. Data processing involved converting to Beijing time and applying quality control procedures including regional extreme value checks and temporal consistency verification [19]. For extreme value checks, data from national meteorological stations were used as reference to calculate hourly precipitation means and standard deviations, with critical values set at mean $\pm$ 3 standard deviations; data exceeding these thresholds were flagged as abnormal. Temporal consistency checks identified anomalies when three or more consecutive hours had equal precipitation amounts within 0–0.5 mm or equal amounts greater than 0.5–1 mm. Following these procedures, all stations achieved data availability rates above 95%, except for stations Y8344 and Y8317, which had rates around 85%. Overall data completeness was satisfactory. Station averages were calculated for each year, month, day, and hour to represent the study area, excluding calculations when data were missing for any station at a given time.

2.3 Analysis Methods

Precipitation events were identified when hourly precipitation $\geq$ 0.1 mm. Based on this threshold, precipitation amount, frequency, and intensity (ratio of precipitation amount to frequency) were calculated to analyze diurnal variation characteristics [20]. To assess the influence of precipitation intensity categories on diurnal distribution [21], rainfall intensity (R) was classified into four levels: $R \leq 2.0$ mm, 2.1 mm $\leq R \leq$ 4.0 mm, 4.1 mm $\leq R \leq$ 6.0 mm, and $R \geq 6.1$ mm. Precipitation duration was defined as the number of consecutive hours from precipitation onset to cessation [22], with a precipitation process considered ended when no precipitation occurred for two consecutive hours. Process precipitation amount (R) was categorized according to Xinjiang Meteorological Bureau standards [23] as light rain (0.1 mm $\leq$ R $\leq$ 6.0 mm), moderate rain (6.1 mm $\leq$ R $\leq$ 12.0 mm), and heavy to torrential rain (R $\geq$ 12.1 mm). Considering the study area' s time zone [24], daily periods were divided into daytime (09:00-20:00, with 09:00-14:00 as morning and 15:00-20:00 as afternoon) and nighttime (21:00-08:00, with 21:00-02:00 as first half of night and 03:00-08:00 as second half of night), all in Beijing time.

3. Results

3.1 Diurnal Variation Characteristics of Precipitation

3.1.1 Precipitation Amount Figure 2 shows distinct hourly variation patterns across different time scales. On an interannual scale (Figure 2a), high-value zones of hourly precipitation occurred primarily during 19:00-21:00 before 2020, concentrated during 21:00-02:00 in 2020-2021, and shifted to 13:00-20:00 in 2022-2023. Overall, daytime precipitation amounts showed increasing trends, while nighttime amounts generally decreased, indicating that interannual increases favor more daytime and less nighttime precipitation. On a monthly scale (Figure 2b), high-value zones varied by month: May peaked during 11:00-13:00, June during 15:00-03:00, July during 17:00-01:00, August during 21:00-01:00, and September showed a bimodal pattern with peaks at 11:00-18:00 and 19:00-21:00. These shifts suggest that as the season progresses, precipitation increases during the first half of the night and decreases in the morning. Daily variation (Figure 2c) shows a unimodal distribution peaking at 18:00, with high values during 18:00-24:00 and low values during 07:00-10:00. In summary, precipitation amount increases during daytime on annual scales, during the first half of the night on monthly scales, and peaks in the afternoon to first half of the night on daily scales.

3.1.2 Precipitation Frequency Figure 3 reveals that cumulative precipitation frequency evolution closely mirrors precipitation amount. Interannually (Figure 3a), precipitation events occurred most frequently during 01:00-07:00, except in 2020 when they peaked during 22:00-02:00. Overall, daytime frequencies showed decreasing trends while nighttime frequencies increased, indicating that as the warm season progresses, precipitation events become more nocturnal. Monthly variation (Figure 3b) shows high values during 17:00-01:00, with peaks at 01:00 in June, 02:00 in July, and 01:00 in August. Daily variation (Figure 3c) displays a unimodal distribution peaking at 02:00 (0.39 events) with a valley at 06:00-10:00. Thus, precipitation frequency increases significantly during afternoon to first half of the night across annual, monthly, and daily scales.

3.1.3 Precipitation Intensity Figure 4 shows precipitation intensity diurnal variation differs notably from amount and frequency. Interannually (Figure

4a), high values concentrated during 13:00-20:00 before 2020, and during 20:00-02:00 in other years. Intensity increased most during 10:00–14:00 and decreased most during 21:00–02:00, with morning hours showing the most significant increasing trends, indicating that interannual increases enhance morning intensity while reducing afternoon intensity. Monthly variation (Figure 4b) shows high values during 11:00–01:00, peaking at 17:00 (1.13 mm $\cdot$ h^{-1}) with the lowest intensity during 05:00–10:00. Intensity increased markedly during the first half of the night but decreased during the second half as the season progressed. Daily variation (Figure 4c) shows a unimodal pattern with minimal fluctuation, peaking at 13:00 and reaching a valley at 06:00–10:00. Overall, intensity increases significantly in the morning on annual scales and more prominently during the first half of the night on monthly and daily scales.

3.1.4 Correlation Analysis Table 1 demonstrates that warm season precipitation amount correlates best with frequency across all time scales, passing the 0.01 significance test, followed by correlations with intensity, while frequency-intensity correlations are weaker. On annual scales, amount-frequency correlation reaches 0.91 (significant at 0.01), amount-intensity correlation is 0.63 (significant at 0.05), and frequency-intensity correlation is 0.42 (not significant). Monthly and daily scales show similar patterns, with amount-frequency correlations of 0.89 and 0.88 (both significant at 0.01), respectively. Only hourly-scale frequency-intensity correlation passes the 0.05 significance test. These results indicate that warm season precipitation amount in the Bayanbuluke Basin is primarily influenced by precipitation frequency.

3.2 Rainfall Intensity Variation Characteristics

Analysis of different intensity levels reveals that the R $\leq$ 2.0 mm category accounts for the most precipitation amount and highest frequency, representing 49.52% of total precipitation and 87.28% of total frequency. The 2.1 mm $\leq$ R $\leq$ 4.0 mm category follows, while R $\geq$ 6.1 mm events, though least frequent, contribute substantially to total precipitation. Figure 5 shows consistent diurnal patterns between amount and frequency across intensity levels. For R $\leq$ 2.0 mm, both amount and frequency peak at 23:00 and 20:00, respectively, with high values during 17:00–01:00 and low values during 04:00–14:00. For 2.1 mm $\leq$ R $\leq$ 4.0 mm, both metrics show two high-value periods at 11:00–13:00 and 18:00–03:00, with low values during 04:00–10:00, peaking at 09:00. For 4.1 mm $\leq$ R $\leq$ 6.0 mm, both peak at 24:00 and reach valleys at 15:00. For R $\geq$ 6.1 mm, both show peaks at 24:00 and valleys at 08:00, with high values during 15:00–01:00 and low values during 21:00–11:00. Thus, all intensity levels show higher precipitation amounts and frequencies during 17:00–01:00, while 06:00-10:00 shows the opposite pattern.

3.3 Process Precipitation Variation Characteristics

3.3.1 Temporal Analysis Figure 6 shows that annual process precipitation occurrence and duration are dominated by the 0.1 mm $\leq$ R $\leq$ 6.0 mm category, contributing 52.37% of total precipitation in some years and 48.42% in others. The R $\geq$ 12.1 mm category, while least frequent (1.07% of total events), contributes most significantly to total precipitation. Monthly analysis reveals similar patterns, with 0.1 mm $\leq$ R $\leq$ 6.0 mm events dominating frequency but R $\geq$ 12.1 mm events providing the largest contribution. Table 2 shows that R $\geq$ 12.1 mm events average 8.53 mm per occurrence with 8.05 hours duration, contributing 33.67% to total precipitation despite representing only 1.07% of events. The 6.1 mm $\leq$ R $\leq$ 12.0 mm category contributes 33.12% to total precipitation. These results demonstrate that while light rain processes dominate frequency, heavy to torrential rain processes drive precipitation totals.

3.3.2 Diurnal Characteristics Table 3 reveals that daytime precipitation amount, frequency, and duration exceed nighttime values by 17.83%, 28.57%, and 13.26%, respectively. The afternoon period (15:00–20:00) shows maximum values, accounting for 32.56% of total precipitation, 31.22% of total frequency, and 30.01% of total duration. The first half of the night contributes most to the R $\geq$ 12.1 mm category (36.98% of its total amount) and shows the longest duration. Precipitation intensity is highest during the first half of the night (2.99 $\text{mm} \cdot \text{event}^{-1}$), followed by afternoon (2.47 $\text{mm} \cdot \text{event}^{-1}$). Thus, warm season precipitation is dominated by daytime events, with afternoon showing the highest contribution and longest duration, while the first half of the night contributes most to heavy precipitation.

3.4 Variation Characteristics of Different Precipitation Durations

3.4.1 Precipitation Amount Variation Long-duration precipitation contributes most to warm season totals in the Bayanbuluke Basin, with cumulative amount increasing with duration (Figure 7). Events lasting >12 hours contribute 22.9% to total precipitation, while 1-3 hour events contribute only 5.84%. The 9–12 hour duration provides the best precipitation type, with cumulative amount reaching 938.07 mm (57.15% of total). Diurnally, durations $ $6 hours peak during afternoon (15:00–20:00), while 7–10 hour events peak at 21:00. Events lasting 11–12 hours show high values during 19:00–23:00, and >12 hour events concentrate during 17:00–02:00, peaking at 03:00 with 21.69 mm. Thus, short-duration precipitation peaks in afternoon, while long-duration events peak in the first half of the night.

3.4.2 Precipitation Frequency Variation Short-duration precipitation dominates warm season frequency (Figure 7). Events lasting 1–3 hours occur most frequently (40.48% of total events), with 4–6 hour events second (19.95%). Diurnally, 1–6 hour events occur 2.84 times more frequently during daytime, peaking during 15:00–20:00. Events lasting 4–6 hours show peak differences, with maximum frequency at 15:00 and minimum at 05:00-06:00. The 7-10 hour category occurs 84 times, with daytime frequency 1.38 times nighttime frequency and peaks at 18:00. Events lasting 11-12 hours occur only 23 times, mostly during 17:00-02:00. The >12 hour category occurs 17 times, predominantly at night. Thus, short-duration events peak in afternoon, while long-duration events favor the first half of the night.

4. Discussion

This study reveals that warm season precipitation amount in the Bayanbuluke Basin is strongly influenced by precipitation frequency, with both showing consistent diurnal patterns. High-value zones concentrate during 18:00-21:00, and rainfall intensity above 4 $mm \cdot h^{-1}$ occurs primarily during the first half of the night, consistent with previous research [12-13, 27]. Compared to the nearby Ili River Valley, both regions experience predominantly short-duration precipitation, but the Ili Valley shows greatest contributions from 1-3 hour events [28], while Bayanbuluke Basin' s precipitation is dominated by 0.1 mm $\leq$ R $\leq$ 6.0 mm intensity events. Process precipitation analysis shows that 6.1 mm $\leq$ R $\leq$ 12.0 mm events occur most easily in afternoon with large amounts and long duration, while R $\geq$ 12.1 mm events, though most probable in afternoon, contribute most during the first half of the night with longest duration.

Long-duration precipitation, particularly events lasting >12 hours, contributes most to total amount. Warm season precipitation in the Tianshan Mountains is mainly influenced by the Asian subtropical westerly jet; when the jet shifts southward, systematic weather with longer precipitation duration occurs, while northward shifts produce shorter convective weather [29]. The Ili River Valley' s west-east oriented trumpet-shaped topography blocks and lifts westerly and northerly flows, favoring short-duration convection [30], whereas the high-altitude, three-sided mountainous Bayanbuluke Basin is more susceptible to systematic weather from southerly flows [31]. Monthly analysis shows July has the longest high-value duration (15:00-20:00), June 次之 (17:00-01:00), and September the shortest (11:00-18:00 and 19:00-21:00), suggesting July may be dominated by systematic weather while September experiences more convective activity.

The study also demonstrates that different time scales reveal distinct diurnal characteristics: annual scales show increasing daytime precipitation amount and intensity, monthly scales show increasing nocturnal precipitation, frequency, and intensity, and daily scales show stronger precipitation events favoring afternoon to first half of the night, indicating higher afternoon convective potential. Future research will explore spatial patterns, topographic influences, and incorporate satellite data and numerical simulations to better understand the physical mechanisms underlying warm season precipitation diurnal variation in the Bayanbuluke Basin.

5. Conclusions

1) Precipitation amount, frequency, and intensity show consistent but scale-dependent diurnal variation characteristics. On annual scales, amount and intensity increase during daytime while frequency increases at night. On monthly scales, all three metrics increase during nighttime. Within a day, the 18:00–24:00 period features high precipitation amount, frequency, and intensity, while 07:00–10:00 shows the opposite pattern.

2) Precipitation amount, frequency, and intensity show consistent temporal distributions, but amount-frequency correlations are strongest, indicating that warm season precipitation amount is primarily influenced by frequency. The R $\leq$ 2.0 mm intensity category contributes most to precipitation amount and frequency. The 21:00–01:00 period shows large precipitation amounts and high frequency, with R $\geq$ 12.1 mm events contributing most to total precipitation despite their rarity.

3) Process precipitation is dominated by 0.1 mm $\leq$ R $\leq$ 6.0 mm events, but R $\geq$ 12.1 mm events contribute most to total amount. The 6.1 mm $\leq$ R $\leq$ 12.0 mm category occurs most frequently in afternoon with large amounts and long duration, while R $\geq$ 12.1 mm events show highest contribution and longest duration during the first half of the night.

4) Precipitation diurnal cycles are closely related to duration. Short-duration (1-3 h) events occur most frequently during 15:00–20:00, while long-duration (>12 h) events contribute most to total amount and occur primarily at night. The diurnal variation curve and high-value periods of process precipitation can be distinguished by two different precipitation persistence types.

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