atmosphere

Article

Characteristics of Hourly Extreme Precipitation over the Eastern Extension of the Tibetan Plateau

Yuan Chen [1], Yang Zhu [1], Wei Luo [1], Ting Duan [2,*] and Quanliang Chen [3]

1 CHN Energy Daduhe Big Data Service Co., Ltd., Chengdu 610041, China; yuan.chen.ag@chnenergy.com.cn (Y.C.); yang.zhu@chnenergy.com.cn (Y.Z.); wei.luo.ap@chnenergy.com.cn (W.L.)
2 Guanghan College, Civil Aviation Flight University of China, Guanghan 618307, China
3 Plateau Atmospheric and Environment Laboratory of Sichuan Province, School of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu 610225, China; chenql@cuit.edu.cn
* Correspondence: dtqxt@cafuc.edu.cn

Abstract: The eastern extension of the Tibetan Plateau (EETP) has complex terrain, unique climate characteristics, and significant regional differences. Based on the hourly precipitation data from 444 stations over the EETP, the characteristics of the extreme precipitation event (EPE) diurnal cycle over the EETP and their regional differences during the warm season (May–September) have been indicated and revealed in this study. The mean duration of EPEs at most stations over the EETP is over 6 h, except for some stations in the eastern part of the Tibetan Plateau and Yunnan province. In addition to the Qinba Mountain area, EPEs developed rapidly in most stations. EPEs with long (short) durations usually start at night (afternoon). But in the southwestern part of the Sichuan Basin (eastern part of the Tibetan Plateau), long-duration EPEs and short-duration EPEs often start at night (afternoon to early night). Meanwhile, the long-duration EPEs lead to the nocturnal diurnal peaks and eastward propagating features of extreme precipitation amount (EPA) over the EETP. In the Sichuan Basin (the eastern part of the Tibetan Plateau), the onset and peak moments of total EPEs show a single diurnal peak and appear at midnight (late afternoon to early night). The onset and peak moments of EPEs in the Yunnan–Guizhou Plateau and the Qinba Mountain area exhibit two diurnal peaks, one at midnight and the other from afternoon to early night. Over the EETP, for the long-duration EPEs, the peak moments are often delayed by 2–3 h compared to the start moment, while for the short-duration EPEs, the peak moment and the start moment almost coincide.

Keywords: hourly extreme precipitation; diurnal cycle; regional differences; the eastern extension of the Tibetan Plateau

Citation: Chen, Y.; Zhu, Y.; Luo, W.; Duan, T.; Chen, Q. Characteristics of Hourly Extreme Precipitation over the Eastern Extension of the Tibetan Plateau. *Atmosphere* **2024**, *15*, 170. https://doi.org/10.3390/atmos15020170

Academic Editors: Michael L. Kaplan, Zhiqiang Gong, Gang Huang and Chao Li

Received: 12 December 2023
Revised: 16 January 2024
Accepted: 26 January 2024
Published: 29 January 2024

1. Introduction

Extreme precipitation refers to precipitation events with low occurrence frequency at a given place in history, and it could have serious environmental, social, and even political impacts [1]. In a warmer climate, the water-holding capacity of the atmosphere will be enhanced, leading to increased evaporation and atmospheric humidity [2]. Faster hydrological cycles can affect the frequency and intensity of extreme precipitation [3–5]. Previous studies have found a significant decrease in the number of days of rainfall, a significant increase in the intensity of precipitation in most areas, and significant regional differences in the spatial distribution of extreme precipitation in China [6–10]. Extreme precipitation in areas with complex terrain usually has unique evolution characteristics. Topography not only plays an important role in the generation and development of extreme precipitation but also has a significant influence on the distribution of extreme precipitation; for example, short-term extreme precipitation variations are greater at high altitudes than at low altitudes, but extreme precipitation extremes are much lower at high altitudes than at low altitudes [11–14]. The Tibetan Plateau is the highest globally, with an average elevation of more than 4000 m. Moreover, the Tibetan Plateau plays an essential role in the regional climate of East and South Asia, as well as in the atmospheric circulation of the Northern Hemisphere [15,16]. The eastern extension of the Tibetan Plateau (EETP) is a transitional zone between the Tibetan Plateau and the eastern plains of China. This region is affected by both the East Asian summer monsoon and the Indian summer monsoon, as well as the circulation over the Tibetan Plateau [17]. Regional circulations and convective activity over the EETP are also strongly influenced by local diurnal thermal contrast near the surface [15]. The elevation difference over the EETP is significant, the terrain is complex, and various landforms are crisscrossed in different regions. Due to the complex terrain, geological disasters caused by extreme precipitation occur frequently in the EETP. During the past several decades, there has been a significant increase in extreme precipitation over the EETP. The contribution of extreme precipitation to total precipitation increased over time, and the climate extremes were enhanced; at the same time, this obvious enhancement is more likely to be found at higher altitudes, hilly, and flat stations [18,19]. Although extreme precipitation has been studied extensively and some valuable results have been obtained, the previous studies on extreme precipitation over the EETP are primarily based on the daily rainfall data and focused on the long-term trend of extreme precipitation in several decades or mainly concentrated on the extreme precipitation with durations at or above the daily scale [20,21].

Compared to extreme precipitation at daily and multi-day time scales, extreme precipitation at hourly scales can properly reflect the intensity and frequency of precipitation and describe more details of heavy precipitation processes [22]. Moreover, hourly extreme precipitation is often the leading cause of disasters, and it can cause colossal life and property losses in a short period [23]. In North America [24], Europe [25], parts of China [26], and Southeast Asia [27], more and more analyses based on observed data show that the frequency and intensity of hourly extreme precipitation have significantly increased. In addition to studying the trend of hourly extreme precipitation, the diurnal variation characteristics of hourly extreme precipitation have also received extensive attention. Li et al. [28] analyzed the characteristics of hourly extreme precipitation duration in China and found that the average duration of extreme precipitation events exceeds 12 h in the coastal regions, Yangtze River valley, and the eastern slope of the Tibetan Plateau. Meanwhile, extreme precipitation events develop more rapidly in mountain regions with large elevation differences than in plain areas. The hourly extreme precipitation in the lower reaches of the Yangtze River Basin mainly occurs in the afternoon. With the increase in duration, the extreme precipitation events start later [29]. Previous studies have indicated that hourly extreme precipitation over the EETP has shown an increased trend of both frequency and intensity [30,31]. Therefore, it is necessary to provide more detailed information on extreme precipitation at sub-daily time scales over the EETP.

Meanwhile, the observation stations adopted by previous studies on hourly extreme precipitation characteristics in the SETP were distributed sparsely. Limited by the station density and complex terrain, which significantly influences rainfall distribution, we do not know enough about the characteristics of EETP hourly extreme precipitation. Therefore, the observation stations with a higher density are employed to analyze the hourly-scale characteristics of extreme precipitation in this area. We will focus on addressing such issues as follows: (1) the mean features of hourly extreme precipitation over the EETP during the warm season; (2) the daily cycle of extreme precipitation over the EETP; and (3) regional differences of EETP hourly extreme precipitation over complex terrains. These findings provide a reference for understanding the possible mechanism of extreme precipitation over the EETP and evaluating high-resolution models of extreme precipitation in the future.

2. Data and Methods

2.1. Data

In this study, the observational hourly rainfall data from 2004 to 2017 at 625 stations in the EETP are used, which were collected and quality-controlled by the National Meteorological Information Centre of China Meteorological Administration, including consistency test and extreme value test for climate background and single station. This dataset is widely used in studies of hourly precipitation and hourly extreme precipitation in China [30,32,33]. Then, further quality control [34] has also been applied as follows: Firstly, the daily rainfall amount (R1) is calculated by the hourly data. The daily rainfall amount from the daily precipitation dataset of the same stations, which is also from the National Meteorological Information Centre of China Meteorological Administration, is R2; if $|R1 - R2| > R2/10$, the records of hourly data for this particular day are regarded as missing values, else are regarded as effective values; if the effective observation is less than 85% of the warm season, the hourly records in this year are marked as missing values. Finally, 444 stations without a missing year during 2004–2017 were chosen to analyze the hourly extreme precipitation characteristics over the EETP. The distribution of stations is shown in Figure 1.

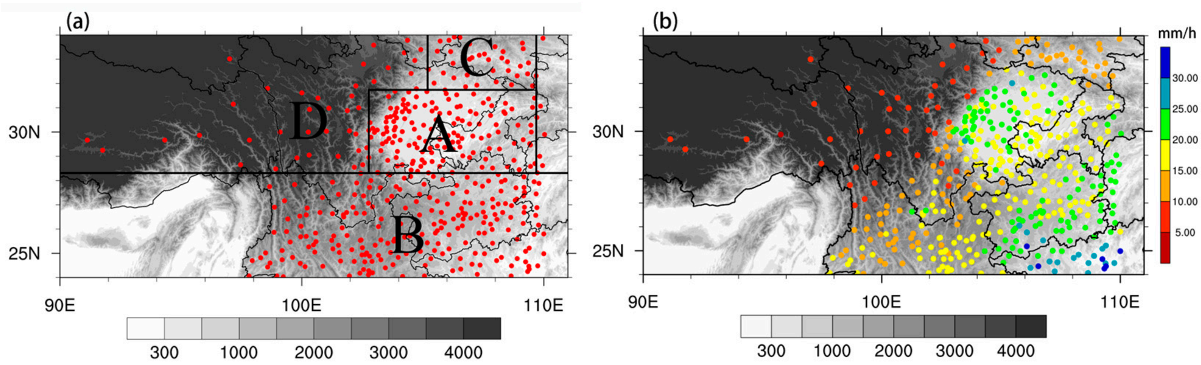

Figure 1. (**a**) Eastern extension of the Tibetan Plateau and distribution of the selected 444 stations and four sub-regions, Zone A: Sichuan Basin; Zone B: Yunnan–Guizhou Plateau; Zone C: Qinba Mountain area; and Zone D: Eastern part of the Tibetan Plateau; (**b**) spatial distribution of hourly extreme precipitation thresholds for each station (units: mm/h). The grey shading indicates the elevation (units: m).

2.2. Methodology Used to Select Extreme Precipitation Events

The 99th percentile of the historical hourly precipitation time series for the warm season during 2004–2017 was used as the threshold for extreme precipitation at each station, based on the cumulative frequency distribution (CFD) method [6]. Figure 1b shows the hourly extreme precipitation thresholds for each station over the EETP. Most stations over the EETP have thresholds above 15 mm/h. Especially in the western part of the Sichuan Basin and the southern part of Guizhou Province, thresholds in these two areas exceed 20 mm/h, while stations in the eastern part of the Tibetan Plateau have thresholds of 5–10 mm/h. The characteristics of EETP hourly extreme precipitation are analyzed by selecting hourly extreme precipitation as events. Extreme precipitation events (EPEs) are defined as a sequence without any intermittence, and every hourly precipitation in this sequence is $\geq$0.1 mm/h; then when at least one of the hours in the sequence exceeds the EP threshold for the station, the sequence is counted as an EPE. The EPEs are picked out separately at each station.

2.3. Methodology Used for Mean EPE Features

Define the hours between the start and end of the EPE as the EPE duration. EPEs are classified into long-duration EPEs (duration $\geq$ 6 h) and short-duration EPEs (duration < 6 h) based on the duration of the EPE. The hourly rainfall amount is defined as the total rainfall amount divided by the non-missing hours. The extreme precipitation amount (EPA) is the accumulated EP rainfall divided by the total hours in the warm season from 2004 to 2017 at each station.

2.4. Methodology Used for Diurnal Cycle of EPE and Its Regional Difference

With the selected EPEs, we defined each event its starting moment as the onset moment, and the peak moment of an EPE is the hour (00:00~23:00 Beijing time) when the precipitation reaches the maximum value within the duration. Using the onset moments and peak moments of the EPEs, we analyzed the characteristics of the diurnal cycle of the EPEs and the details of the EPEs over the EETP. Due to the complex terrain, the extreme precipitation has unique evolution characteristics. To research the regional differences in hourly extreme precipitation, the region is divided into four large topographic zones: Zone A: Sichuan Basin; Zone B: Yunnan–Guizhou Plateau; Zone C: Qinba Mountain area; and Zone D: Eastern part of the Tibetan Plateau (Figure 1a). Figure 2 shows the steps used in this paper.

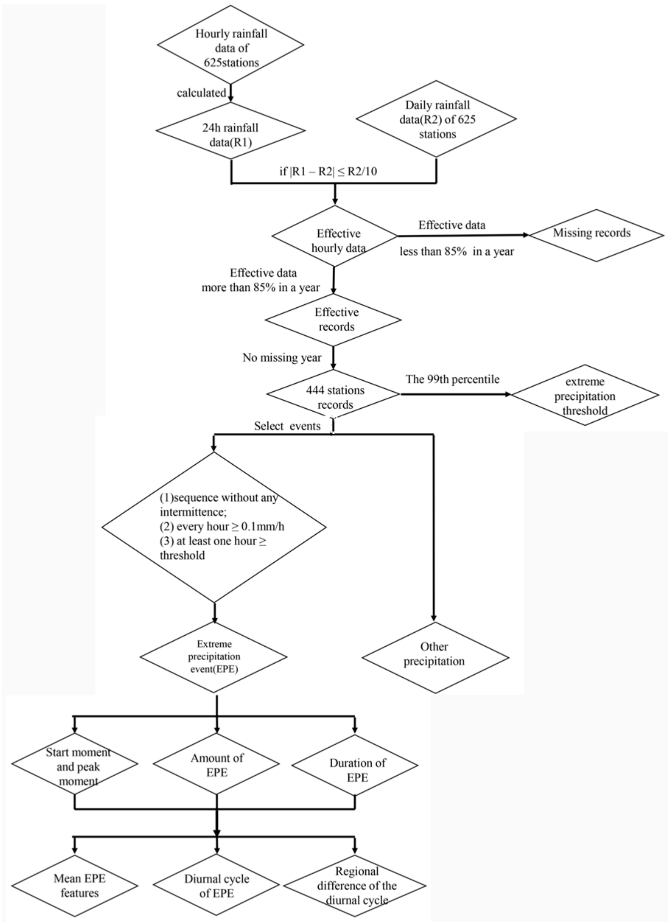

Figure 2. The steps used in this paper.

3. Results

3.1. Mean EPE Features

Figure 3a illustrates the average duration of EPE over the EETP. Generally, there was significant regional difference in the duration of EPE over the EETP. In the eastern part of the Tibetan Plateau and most parts of Yunnan Province, the average duration of EPE is short, usually below 6 h. The average duration of EPE in the western part of the Sichuan Basin, the Guizhou Province, is around 6–9 h. The areas with the longest average duration of EPE are located in the northeastern Sichuan Basin and the Qinba Mountain area, above 9 h, with some stations having an average duration of above 12 h. The time taken from the start to the peak of an EPE significantly impacts extreme precipitation disaster preparedness and management. As shown in Figure 3b, most of the stations on the EETP require a short time, which is less than 2 h, to reach the peak of an EPE; meanwhile, the stations in the Qinba Mountain area, which require a longer time, taking more than 3 h to reach the peak.

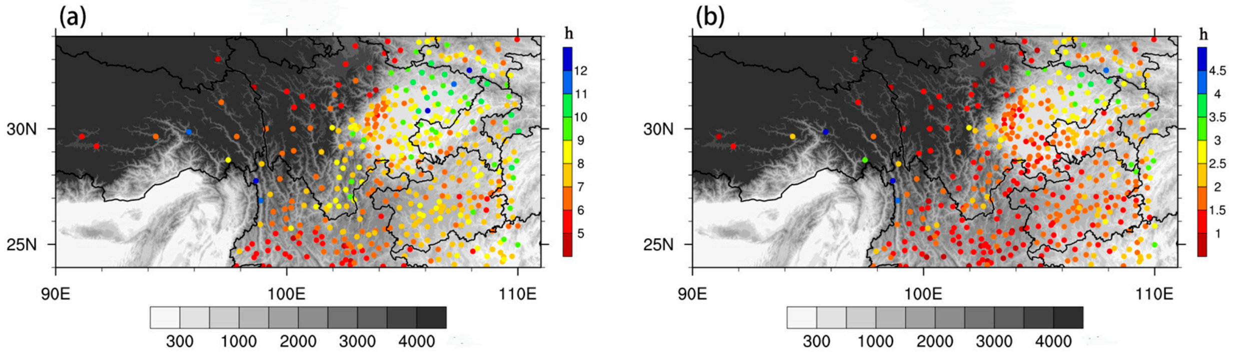

Figure 3. Distribution of (**a**) average rainfall duration (units: h) for EPEs and (**b**) the average time required to reach the peak after the start of the EPEs (units: h) in the warm seasons (May–September) during 2004–2017.

Figure 4 shows the percentages of the EPA to the PA over the EETP during the warm season. The percentage of the total EPA shows a large center with a percentage >30% located over the western Sichuan Basin. In contrast, the percentages in most parts of the Yunnan Province and the eastern part of the Tibetan Plateau are much smaller, with the percentage less than 25% (Figure 4a). In addition, with the long duration, the EPA contributes more than 60% of the total EPA in the eastern part of the Sichuan Basin, the Panxi area, the Qinba Mountain area, and the southern part of Guizhou. Meanwhile, the eastern part of the Tibetan Plateau and the Yunnan Province is dominated by short-duration EPE, which contributed over 60%. The contribution of EPA with long and short durations in the central part of the Sichuan Basin and the northern part of Guizhou is comparable, and both are around 50% (Figure 4b,c).

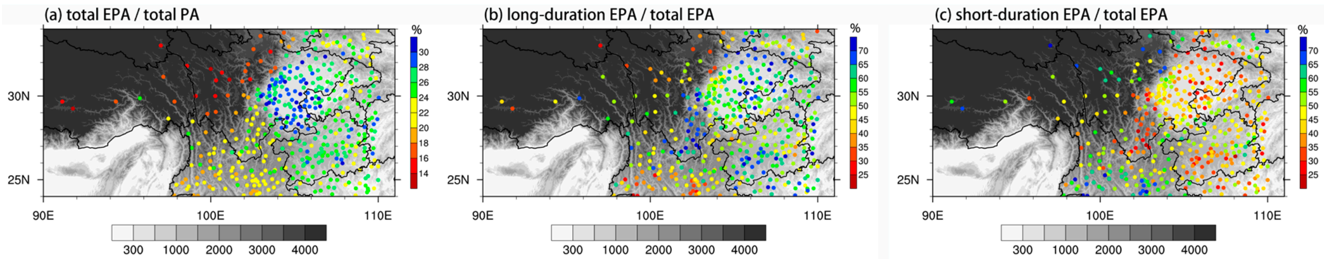

Figure 4. The distribution of contribution of the total EPA to the total PA (**a**) and contribution of the EPA with long (**b**) and short (**c**) durations to the total EPA in the warm season over the EETP (units: %).

3.2. Diurnal Cycle of EPE over the EETP

To further analyze the diurnal variation in EPE over the EETP, the peak time corresponding to the onset moments and peak moments of EPE is shown in Figure 5. As shown in Figure 5a, the onset moment of EPE with long duration on the EETP occurs from late afternoon to midnight (17:00–05:00 Beijing time). It can be noted that the onset moment of EPE with long-duration diurnal peaks in the Sichuan Basin and Guizhou appears predominantly between 20:00 and 05:00 Beijing time. On the eastern part of the Tibetan Plateau, the long-duration EPE starts earlier, at 17:00–20:00 Beijing time. For EPE with short duration, in the western and southern parts of the Sichuan Basin, it is still mostly started in the nighttime (20:00–02:00 Beijing time). In contrast, most EPEs with short duration at other stations on the EETP are primarily started in the afternoon and dusk (14:00–20:00 Beijing time), which may be caused by the instability of the lower layer caused by surface radiation heating in the afternoon (Figure 5b). From Figure 5c, in terms of the peak moment of EPE, the EPEs with long duration are more likely to reach the peak at night and midnight (20:00–05:00 Beijing time) in the eastern part of the Tibetan Plateau, western Sichuan Basin, and Yunnan Province, while in the northern Sichuan Basin, Qinba Mountain area, and eastern Guizhou, the peak moments of long duration EPE are primarily in the early morning and morning periods (05:00–11:00 Beijing time). The spatial distribution of the peak moment of short-duration EPEs is similar to the onset moment (Figure 5b,d), and the peak and onset moments of short-duration EPEs are basically in the same period over the EETP. The short-duration EPEs at most stations mainly reach their peaks in the afternoon and dusk (14:00–20:00 Beijing time), while the short-duration EPEs in the western and southern Sichuan Basin mostly reach their peaks at midnight (Figure 5d).

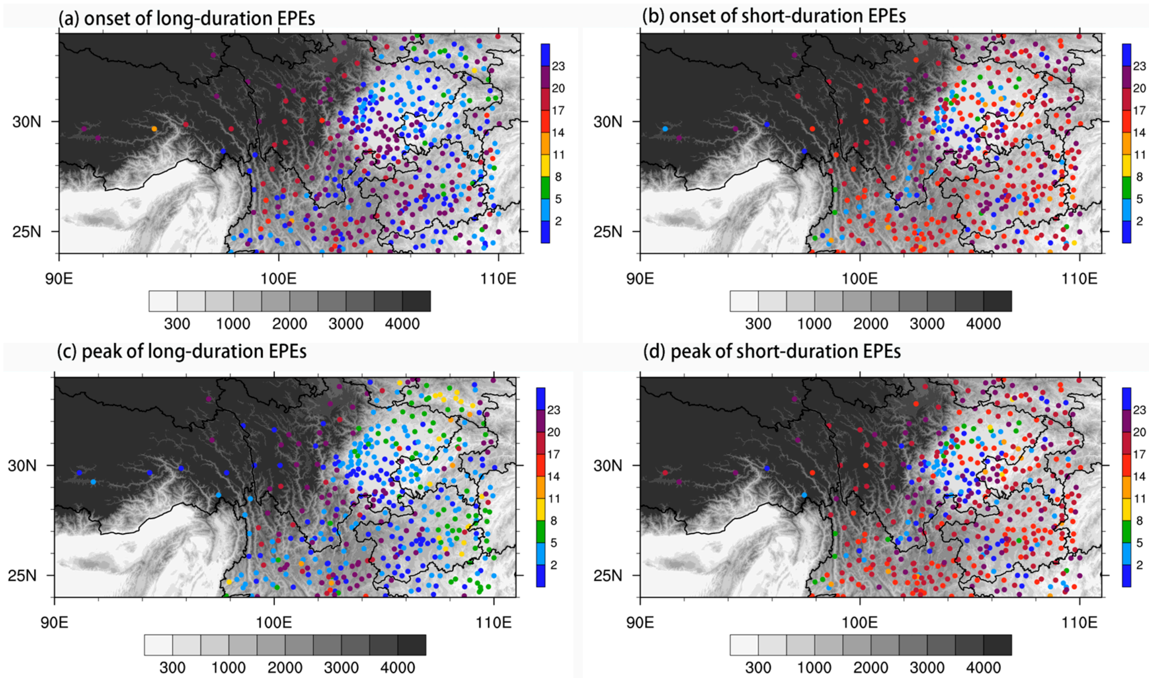

Figure 5. The peak time of diurnal variation in the onset moment (**a**,**b**) and the peak moment (**c**,**d**) of the long-duration EPEs (**a**,**c**) and the short-duration EPEs (**b**,**d**) over the EETP in the warm seasons during 2004–2017 in Beijing time.

From Figure 6a, the total EPA diurnal peaks over the EETP show an apparent eastward propagation, which begins at 17:00 Beijing time and ends at 09:00 Beijing time the next day. Starting from 16:00 Beijing time, the total EPA reaches its maximum at about 100° E, and then the total EPA spreads eastward until 09:00 Beijing time, spreading to 110° E. The maximum EPA occurs at night over the regions west of 104° E, which may be caused by the instability caused by the radiative cooling at the top of the cloud. The eastward propagation at night may be affected by the clockwise rotation of the southwest wind at the lower level [35,36]. The long duration of EPA over the EETP is consistent with the total EPA, and there is also a characteristic that the peak propagates eastward from 17:00 Beijing time to 09:00 Beijing time (Figure 6b). In contrast, the peak of short-duration EPA in the area east of 104° E shows a predominant diurnal peak in the afternoon and dusk, about 15:00–20:00 Beijing time. However, the short-duration EPA also has the characteristics of peak eastward propagation in the area west of 104° E, from 14:00 Beijing time to 03:00 Beijing time (Figure 6c). The activity of mesoscale convection systems (MCSs) with a short lifespan on the eastern slopes of the plateau is probably the main cause of this situation. Under the influence of the latitudinal circulation, the MCSs generated in the late afternoon on the eastern slopes of the plateau moved eastward to the western Sichuan Basin during the night, while the descending airflow in the area east of 104° E prevented it from continuing to develop eastward [37]. It was indicated that the characteristics of the peak of EPA over the EETP propagating eastward at night are mainly determined by long-duration EPEs.

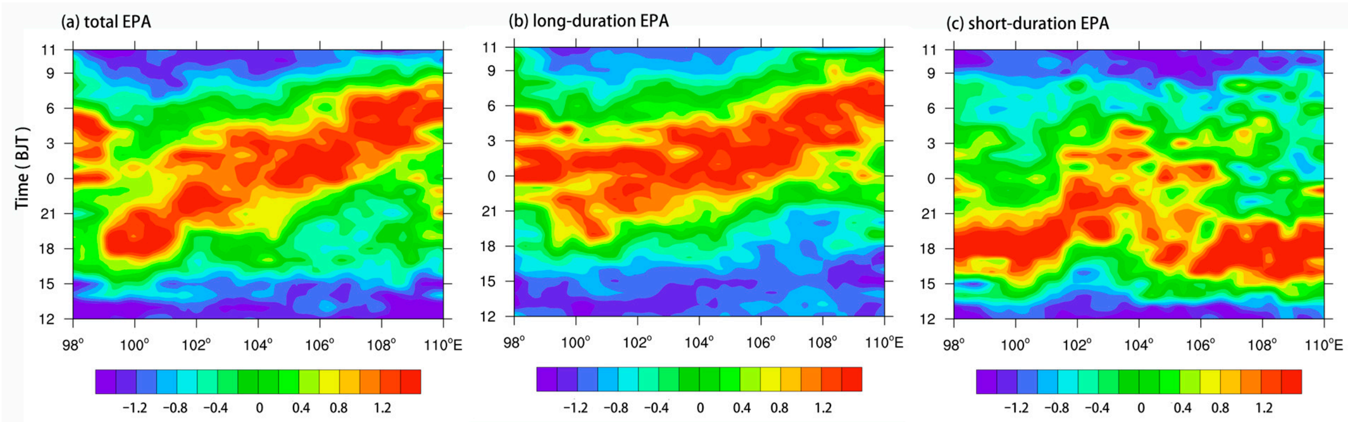

Figure 6. The normalized time–longitude distribution of the total EPA (**a**), and the EPA with long (**b**) and short (**c**) duration regionally averaged over the EETP in the warm season during 2004–2017.

Figure 7 shows the normalized time–longitude distribution of EPA over the EETP. It can be seen that the EPA from south to north over the EETP occurs mainly in the night to early morning (00:00–06:00 Beijing time), only near the 34° N, the diurnal peak of EPA occurs between 18:00 and 23:00 Beijing time. It can be noted that between 28 and 32° N, which is the latitude where the Sichuan Basin is located, the EPA appears a northward propagation of the peak, with the peak first appearing around 28° N at around 21:00 and then propagating northward until 04:00–06:00 Beijing time, when the peak propagates to 32° N (Figure 7a). This suggests that the EPA in the Sichuan Basin has an apparent southwest-to-northeast propagation during the warm season. In previous studies, this unique propagation feature was also present for precipitation in the Sichuan Basin [38]. As shown in Figure 7b, the long-duration EPA shows very similar latitude–time distribution to the EPA. However, the peaks of the short-duration EPA over the EETP occur mainly in the late afternoon and evening from 15:00 to 21:00 Beijing time, and at 28–30° N, mainly the southern part of the Sichuan Basin and part of the eastern slopes of the plateau; the peaks also occur around 21:00–00:00 and 03:00 Beijing time (Figure 7c). It can be seen that in the meridional direction, the total EPA and the long-duration EPA are dominated by nocturnal rain over the EETP, but short-duration EPA is mainly concentrated in the late afternoon.

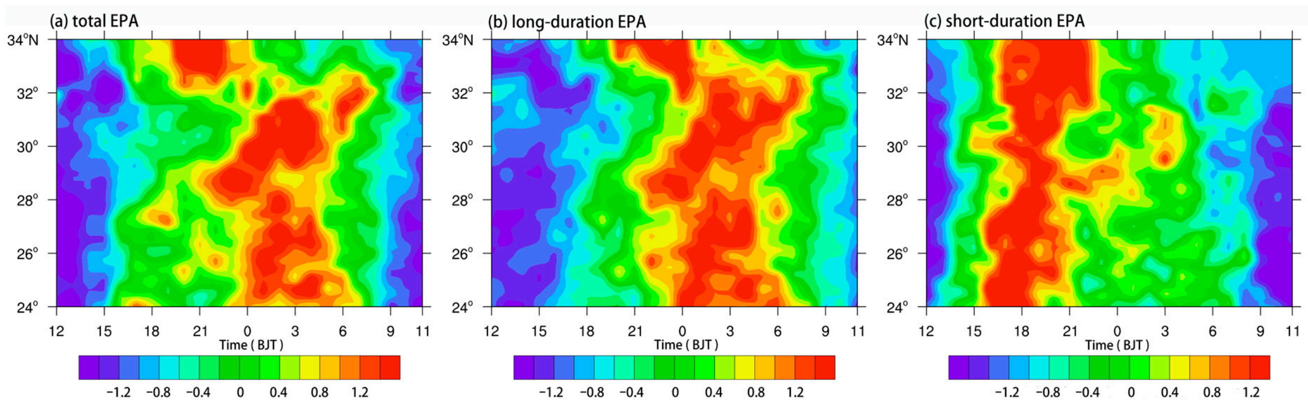

Figure 7. Same as Figure 6, but for the normalized time–latitude distribution.

3.3. *Regional Difference of the Diurnal Cycle over the EETP*

From the previous content, it can be noticed that features of EPE over the EETP have significant regional differences. Figure 8 shows the daily cycle of the normalized times at the onset and peak moment of EPE with different durations regionally averaged over the four subregions. From Figure 8a, it can be seen that for total EPE in the Sichuan Basin, the onset and peak moments are mainly in a single-peak distribution, with the peak of the onset occurring at 01:00, and EPE tends to reach its maximum at 03:00, and the minimum of the onset and peak moments occurring at midday. The diurnal variation in the onset and peak moment of long-duration EPE in the Sichuan Basin is similar to that of total EPE, with maximum occurring at night and minimum at noon, suggesting that the Sichuan Basin is dominated by long-duration EPE. The diurnal variation in the short-duration EPE in the Sichuan Basin shows a bimodal structure of the onset and peak moment. It has a prominent peak at 03:00 at night and a secondary peak at 18:00 in the afternoon, indicating that the short duration EPE is very likely to occur at night and afternoon in the Sichuan Basin, and its minimum still appears at noon. The diurnal variation in the onset and peak moment of total EPE in the Yunnan–Guizhou Plateau shows a bimodal distribution (Figure 8b). There is a peak at 01: 00–03:00 at night and another at 17:00 in the afternoon. The onset and peak moment of long-duration EPE show a unimodal distribution in the Yunnan–Guizhou Plateau, and the maximum value appears at night. For the short-duration EPE in the Yunnan–Guizhou Plateau, the onset and peak moment also show a unimodal distribution, but the maximum value appears in the afternoon. It can be seen that the bimodal structure of the diurnal variation in the onset and peak moment of total EPE in the Yunnan–Guizhou Plateau is mainly dominated by long-duration EPE and short-duration EPE, respectively. Similar to the Yunnan–Guizhou Plateau, the diurnal variation in the onset and peak moment of total EPE in the Qinba Mountain area also shows the bimodal distribution characteristics of one peak at night and one in the afternoon. The EPE, with a long duration in the Qinba Mountain area, consistently tends to occur frequently from late night to the early morning and rarely occurs at noon. In contrast, the short-duration EPE in the Qinba Mountain area appears more often in the afternoon. Compared with the Yunnan–Guizhou Plateau, the diurnal variation in onset and peak moment of the EPE in the Qinba Mountain area shows much more considerable diurnal variability (Figure 8c). All EPEs in the eastern part of the Tibetan Plateau include long-duration EPE and short-duration EPE. The diurnal variation in the onset and the peak moment shows a uniform unimodal distribution. The maximum value appears at 17:00–20:00, and the minimum value appears at noon, indicating that the EPE in the eastern part of the Tibetan Plateau occurs mainly from afternoon to dusk (Figure 8d).

It can be seen that there are some differences in the daily variations in the four subregions. The onset and peak moment of total EPEs in the Sichuan Basin and the eastern part of the Tibetan Plateau show a single-peak distribution (Figure 8a,d), but in the other two regions, there is a bimodal distribution (Figure 8b,c). Meanwhile, the bimodal structure of the Yunnan–Guizhou Plateau and the Qinba Mountain area is caused by long-duration EPE and short-duration EPE, respectively (Figure 8b,c). It is noted that the short-duration EPEs in the Sichuan Basin also show a bimodal structure, with a secondary peak in the afternoon; however, this secondary peak is not clearly represented in total EPEs (Figure 8a). Overall, in the four subregions, the maximum values of the onset moment and peak moment of long-duration EPEs are separated by two to three hours, while for the short-duration EPEs, the maximum values of the onset moment and the peak moment are not delayed.

For total EPEs, it starts first in the eastern part of the Tibetan Plateau, around 17:00–20:00 Beijing time, followed by the Sichuan Basin, the Yunnan–Guizhou Plateau, and Qinba Mountain area, where it occurs around 00:00–02:00. However, for the peak moment of total EPEs, it occurs first in the eastern part of the Tibetan Plateau, then the Sichuan Basin and the Yunnan–Guizhou Plateau reach the peak later, and the Qinba Mountain area is the last. During the daytime, all four subregions show a significant minimum of extreme precipitation, especially at noon. These diurnal cycles are considered to be associated with regional mountain–plain solenoids driven by thermal differences between the plateaus, the highlands, the plains, and the eastward-propagating convective systems originating over the Tibetan Plateau [35,39,40]. Stratus clouds generated by the Tibetan Plateau located in southwestern China prevent solar radiation from reaching the ground during the daytime, inhibiting local thermal convection in the region during the day, resulting in little precipitation and extreme precipitation during the day [41].

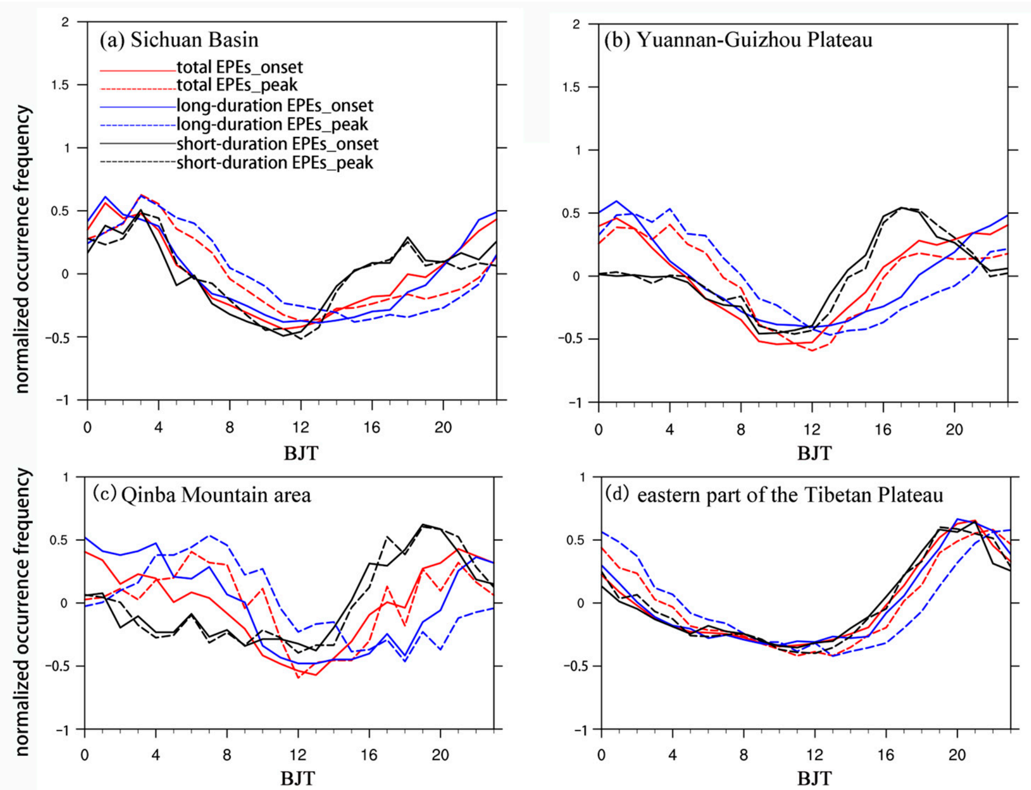

Figure 8. The diurnal cycle of the normalized occurrence frequency at the onset (solid line), peak (dotted line) for the total EPEs (red) and the EPEs with long (blue) and short (black) duration time regionally averaged over four sub-regions of EETP during 2004–2017.

In order to show more clearly and intuitively the diurnal variation in the occurrences of EPE with different durations, Figures 9 and 10 further give the normalized distribution of the start peak moment of EPEs with different durations over the four subregions. As shown in Figure 9a, there are two main types of EPE in the Sichuan Basin. One is an EPE with 4–6 h starting from 02:00 to 03:00 at midnight, and the other is a long EPE with more than 13 h starting at 21:00–02:00 Beijing time. In addition, EPEs with a duration of less than 3 h occur in the Sichuan Basin from 15:00 to 18:00. Still, the probability of occurrence is not as significant as the previous two types of extreme precipitation events. During 08:00–12:00, EPEs do not occur in the Sichuan Basin. Over the Yunnan–Guizhou Plateau, there is dominance of EPEs with a duration of less than 4 h, which starts in the afternoon (15:00–19:00 Beijing time). Meanwhile, the EPEs that started at 17:00–23:00 Beijing time and lasted more than 13 h also occurred more frequently in the Yunnan–Guizhou Plateau (Figure 9b). As shown in Figure 9c, the EPEs with long (short) duration over the Qinba Mountain area mostly start in the night (afternoon), around 20:00–04:00 (17:00–20:00) Beijing time. And almost all other types of EPEs do not occur in the Qinba Mountain area. Compared to the other three subregions, the characteristics of EPEs in the eastern part of the Tibetan Plateau are apparent. It is mainly an EPE that occurs at 16:00–21:00 Beijing time and lasts less than 6 h. EPEs that last longer than 6 h during this period also occur occasionally, while there are no EPEs in the eastern part of the Tibetan Plateau in other periods (Figure 9d).

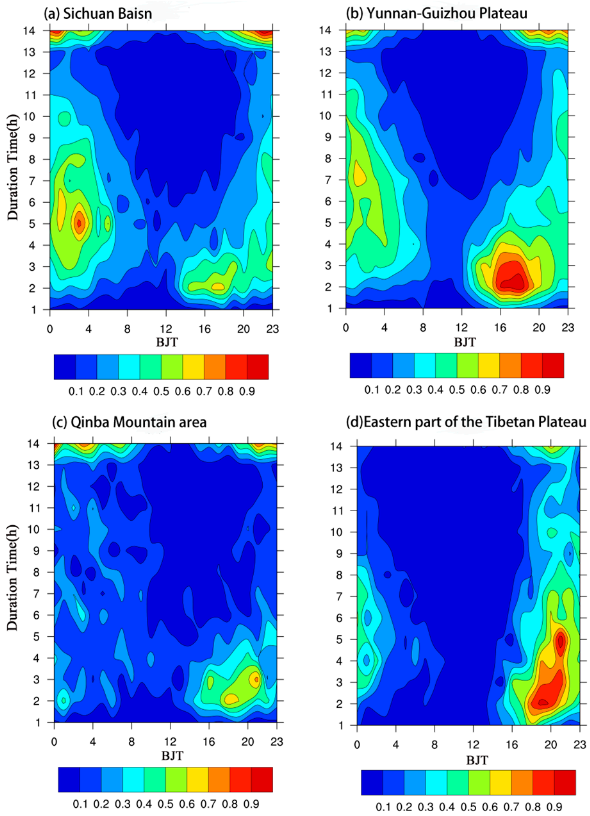

Figure 9. The diurnal cycle of the normalized occurrence frequency at the start time for the EPEs with different duration times over the four sub-regions of EETP.

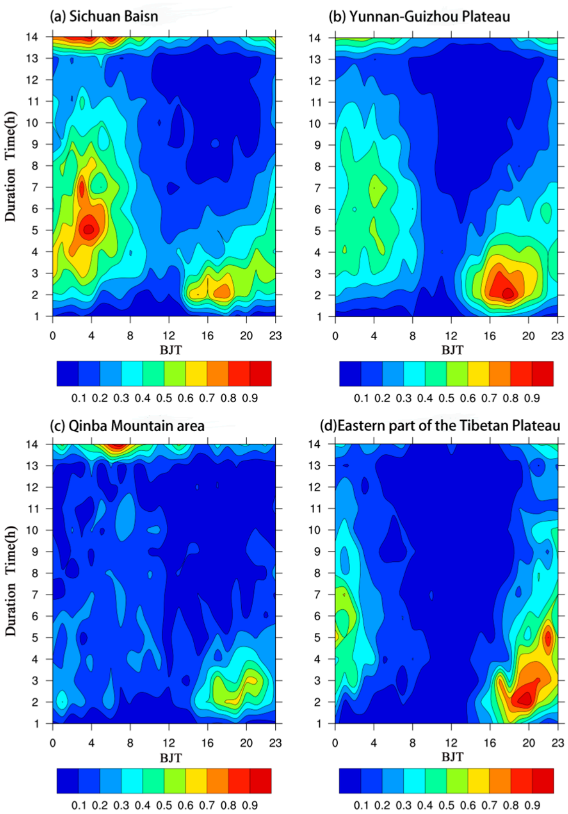

Figure 10. Same as Figure 8, but for the diurnal cycle of the normalized occurrence frequency at the peak time.

From Figure 10a, it can be seen that the peak moments of EPEs in the Sichuan Basin at night are mainly associated with EPEs with a duration of 4–9 h and greater than 13 h, while the peak moments of EPEs in the afternoon are mainly short-duration events with a duration of less than 4 h. At the same time, it can be seen that the peak moment of EPEs occurring at night is 2–3 h later than the start time, especially for long-duration EPEs, which is more pronounced; while in the afternoon, there is no apparent lag between the peak moment and the start moment of the short-duration EPEs. The peak moment and start moment of EPEs in the Yunnan–Guizhou Plateau (Figure 10b) are almost the same in the afternoon, and the peak moment of EPEs with a duration of 4–9 h or with a duration of more than 13 h is mainly at 02:00–06:00 Beijing time. The Qinba Mountain area is mainly dominated by long-duration EPEs that last more than 13 h and peak moments in the morning (06:00–10:00 Beijing time), about 4 h later than the start moment. The second is the EPEs that last less than 4 h and peak moment at 16:00–20:00 Beijing time (Figure 10c). The peak moment of EPEs in the eastern part of the Tibetan Plateau mainly occurs at 16:00–03:00. For the EPEs with a duration of less than 4 h, their peak moment usually occurs at 16:00–21:00 Beijing time. In contrast, the peak moment of EPEs with a duration longer than 4 h is later 2–3 h (Figure 10d).

4. Discussion

In this study, we have revealed the detailed characteristics of hourly extreme precipitation diurnal cycle over the EETP and compared the regional differences of four subregions. Previous studies indicate that over the typical large terrain and downstream regions, such as the Rocky Mountains to the Great Plain in the United States and the Tibetan Plateau to the Sichuan Basin in China, significant delayed diurnal features from the late afternoon to the nighttime are usually found [38,42,43]. This study also found that the EPEs over the EETP have these special diurnal features. But what causes the diurnal cycle and difference is still a question. The Indian summer monsoon and the mid-latitude westerly belt have an important influence on extreme precipitation on the eastern part of the Tibetan plateau; they transport the upstream water vapor from the Indian Ocean eastward to the TP [44]. The accumulation of solar heating near the surface in the afternoon–evening in the eastern part of the Tibetan plateau reaches maximum, easily triggering convection and causing precipitation [45]. The anomalous easterly wind at low levels in the EETP during the afternoon was also an important factor in the formation of heavy precipitation on the eastern slopes of the Tibetan Plateau from the afternoon to the early evening, anomalous easterly winds and topographic effects make it very easy to generate convection [38,40]. Meanwhile, the movement of mesoscale convective systems associated with heavy precipitation is influenced by large-scale circulation in the lower-middle troposphere [46]. Previous studies indicated that the nocturnal EPEs occurring in the Sichuan Basin, Yunnan–Guizhou Plateau, and Qinba Mountains were associated with the diurnal clockwise rotation of the lower-tropospheric circulation, especially the accelerated nocturnal south-westerlies; the anomaly southwesterly wind can cause the mesoscale convective systems to move in a northeast direction in the night [35,41]. In addition, different cloud radiation features in different regions may result in different diurnal cycles of precipitation [47,48].

The complex terrain likewise contributes to the differences in EPEs' diurnal cycle, mainly in the influences of topography on surface and low-level temperature as well as circulation fields [40,49]. The EETP shows a noticeable terrain height difference between the Tibetan Plateau and the other regions, especially in the eastern part of the Tibetan Plateau and Sichuan Basin. The mountain–plain solenoids caused by the heterogeneous heating between the mountain and basin may lead to different diurnal peaks between mountains and basins [35,39,40,45]. The upward branch of the MPS circulation occurs in the eastern part of the Tibetan Plateau in the afternoon, while the Sichuan Basin and the Yunnan–Guizhou Plateau are controlled by the downward motion, which suppresses rainfall over that region. In the evening, updrafts and downdrafts reverse, resulting in nocturnal precipitation east of the eastern slopes of the Tibetan Plateau [35,50]. Moreover, the low-level nighttime anomalous southeasterly wind at EETP forms a substantial topographic uplift on the eastern slope of the Tibetan Plateau, which will also cause EPEs at night in this region [34,48]. Meanwhile, precipitation is often well dependent on elevation and terrain [14,20]. So, does the daily cycle of EPEs over the EETP significantly depend on elevation difference? Previous studies indicate that the Yunnan–Guizhou Plateau may play an essential role in the early night initiation of precipitation over the southwestern Sichuan Basin [48]. Hence, the terrain that plays a vital role in the formation mechanism of EPE over the EETP should be investigated in more detail.

5. Conclusions

Based on the hourly station precipitation data during 2004–2017, the characteristics of EPEs' diurnal cycle over the eastern extension of the Tibetan Plateau (EETP) and their regional differences during warm season in terms of the EPEs start, peak moment, and duration have been studied and indicated. The major conclusions can be summarized as follows:

The duration of EPEs over the EETP has noticeable regional differences. The duration of EPEs is the shortest in the eastern part of the Tibetan Plateau and Yunnan, usually below 6 h, and the longest in the northeastern Sichuan Basin and the Qinba Mountain area, above 9 h. Meanwhile, EPEs over the EETP require a short time to reach the peak, except the Qinba Mountain area, which requires a longer time, taking more than 3 h to reach the peak. The percentage of extreme precipitation amount to total precipitation amount in the Sichuan Basin is the highest, followed by Guizhou Province, and the percentage of extreme precipitation amount to total precipitation amount in the eastern part of the Tibetan Plateau is the lowest. The daily cycle of EPE over the EETP is quite different for different durations. In addition to the eastern part of the Tibetan Plateau, in most stations over the EETP, EPEs with long duration start at night, while the EPEs with short duration start in the afternoon. The EPA over the EETP has apparent characteristics of eastward propagating from afternoon to early morning of the next day, and this feature is mainly dominated by long-duration EPEs.

In the Sichuan Basin and the eastern part of the Tibetan Plateau, the onset and peak moments of total EPEs show a single diurnal peak. The former appears at midnight, and the latter appears in the late afternoon to night. The onset and peak moments of EPEs in the Yunnan–Guizhou Plateau and the Qinba Mountain area both have a bimodal structure of diurnal cycle; long-duration EPEs mainly dominate one peak at night, and the other peak is dominated by short-duration EPEs from afternoon to early night. In the four subregions, the peak moments of long-duration EPEs are often delayed by 2–3 h compared to the start moment; while for the short-duration EPEs, the peak moment and the start moment almost coincide.

Author Contributions: Conceptualization, W.L.; methodology, Y.C. and Y.Z.; software, T.D.; validation, Y.C. and T.D.; formal analysis, Y.C. and Y.Z.; investigation, Q.C.; resources, W.L.; data curation, Y.C.; writing—original draft preparation, T.D.; writing—review and editing, Y.C., Y.Z. and W.L.; visualization, Y.C. and T.D.; supervision, W.L. and Q.C.; project administration, W.L.; funding acquisition, Q.C. and W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was jointly funded by the National Natural Science Foundation (U20A2097, 42075087) and the National Key Research and Development Program of China (2021YFC3000902).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The hourly rainfall data were obtained from the China Meteorological Data Service Centre at https://data.cma.cn/ (accessed on 12 December 2023).

Acknowledgments: All figures were created using the NCAR Command Language (NCL) (2021), http://www.ncl.ucar.edu (accessed on 12 December 2023).

Conflicts of Interest: Authors Yuan Chen, Yang Zhu, and Wei Luo are employed by the company CHN Energy Daduhe Big Data Service Co., Ltd. The paper reflects the views of the scientists and not the company. The authors declare no conflicts of interest.

References

1. Boccolari, M.; Malmusi, S. Changes in temperature and precipitation extremes observed in Modena, Italy. *Atmos. Res.* **2013**, *122*, 16–31. [CrossRef]
2. Trenberth, K.E. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Clim. Chang.* **1999**, *42*, 327–339. [CrossRef]
3. Easterling, D.R.; Meehl, G.A.; Parmesan, C.; Changnon, S.A.; Karl, T.R.; Mearns, L.O. Climate extremes: Observations, modeling, and impacts. *Science* **2000**, *289*, 2068–2074. [CrossRef]
4. Huntington, T.G. Evidence for intensification of the global water cycle: Review and synthesis. *J. Hydrol.* **2006**, *319*, 83–95. [CrossRef]
5. Allan, R.P.; Soden, B.J. Atmospheric warming and the amplification of precipitation extremes. *Science* **2008**, *321*, 1481–1483. [CrossRef]
6. Zhai, P.; Zhang, X.; Wan, H.; Pan, X. Trends in total precipitation and frequency of daily precipitation extremes over China. *J. Clim.* **2005**, *18*, 1096–1108. [CrossRef]
7. Sun, J.; Zhang, F.Q. Daily extreme precipitation and trends over China. *Sci. China Earth Sci.* **2017**, *60*, 2190–2203. [CrossRef]
8. Ding, Z.Y.; Lu, R.J.; Wang, Y.Y. Spatiotemporal variations in extreme precipitation and their potential driving factors in non-monsoon regions of China during 1961–2017. *Environ. Res. Lett.* **2019**, *14*, 024005. [CrossRef]
9. Wang, L.; Qian, Y.; Zhang, Y.; Zhao, C.; Leung, L.R.; Huang, A.; Xiao, C. Observed variability of summer precipitation pattern and extreme events in East China associated with variations of the East Asian summer monsoon. *Int. J. Climatol.* **2016**, *36*, 2942–2957. [CrossRef]
10. Qin, Z.; Peng, T.; Singh, V.P.; Chen, M. Spatio-temporal variations of precipitation extremes in Hanjiang River Basin, China, during 1960–2015. *Theor. Appl. Climatol.* **2019**, *138*, 1767–1783. [CrossRef]
11. Marra, F.; Armon, M.; Borga, M.; Morin, E. Orographic Effect on Extreme Precipitation Statistics Peaks at Hourly Time Scales. *Geophys. Res. Lett.* **2021**, *48*, e2020GL091498. [CrossRef]
12. Avanzi, F.; De Michele, C.; Gabriele, S.; Ghezzi, A.; Rosso, R. Orographic Signature on Extreme Precipitation of Short Durations. *J. Hydrometeorol.* **2015**, *16*, 278–294. [CrossRef]
13. Kang, Y.; Peng, X.; Wang, S.; Hu, Y.; Shang, K.; Lu, S. Observational analyses of topographic effects on convective systems in an extreme rainfall event in Northern China. *Atmos. Res.* **2019**, *229*, 127–144. [CrossRef]
14. Li, Z.; He, Y.; Theakstone, W.H.; Wang, X.; Zhang, W.; Cao, W.; Du, J.; Xin, H.; Chang, L. Altitude dependency of trends of daily climate extremes in southwestern China, 1961–2008. *J. Geogr. Sci.* **2012**, *22*, 416–430. [CrossRef]
15. Ye, D.; Gao, Y. *The Meteorology of the Qinghai-Xizang (Tibet) Plateau*; Science Press: Beijing, China, 1979; pp. 1–278. (In Chinese)
16. Hsu, H.H.; Liu, X. Relationship between the Tibetan Plateau heating and East Asian summer monsoon rainfall. *Geophys. Res. Lett.* **2003**, *30*. [CrossRef]
17. Xu, Y.H.; Wang, Z.D.; Wang, M. *Climate of Southwest China*; Meteorological Press: Beijing, China, 1991. (In Chinese)
18. Hu, W.; Yao, J.; He, Q.; Chen, J. Elevation-Dependent Trends in Precipitation Observed over and around the Tibetan Plateau. *Water* **2021**, *13*, 2848. [CrossRef]
19. Zhang, K.; Pan, S.; Cao, L.; Wang, Y.; Zhao, Y.; Zhang, W. Spatial distribution and temporal trends in precipitation extremes over the Hengduan Mountains region. *Quat. Int.* **2014**, *349*, 346–356. [CrossRef]
20. Ge, G.; Shi, Z.; Yang, X.; Hao, Y.; Guo, H.; Kossi, F.; Xin, Z.; Wei, W.; Zhang, Z.; Zhang, X.; et al. Analysis of precipitation extremes in the Qinghai-Tibetan Plateau, China: Spatio-temporal characteristics and topography effects. *Atmosphere* **2017**, *8*, 127. [CrossRef]
21. Zongxing, L.; He, Y.; Wang, P.; Theakstone, W.H.; An, W.; Wang, X.; Lu, A.; Zhang, W.; Cao, W. Changes of daily climate extremes in southwestern China during 1961–2008. *Glob. Planet. Chang.* **2012**, *80*, 255–272. [CrossRef]
22. Trenberth, K.E.; Dai, A.; Rasmussen, R.M.; Parsons, D.B. The changing character of precipitation. *Bull. Amer. Meteor. Soc.* **2003**, *84*, 1205–1217. [CrossRef]
23. Parry, M.; Parry, M.L.; Canziani, O.; Palutikof, J.; Van der Linden, P.; Hanson, C. *ReportClimate Change 2007-Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC*; Cambridge University Press: Cambridge, UK, 2007; pp. 1–172.
24. Barbero, R.; Fowler, H.J.; Lenderink, G.; Blenkinsop, S. Is the intensification of precipitation extremes with global warming better detected at hourly than daily resolutions? *Geophys. Res. Lett.* **2017**, *44*, 974–983. [CrossRef]
25. Arnone, E.; Pumo, D.; Viola, F.; Noto, L.V.; La Loggia, G. Rainfall statistics changes in Sicily. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2449–2458. [CrossRef]
26. Xiao, C.; Wu, P.; Zhang, L.; Song, L. Robust increase in extreme summer rainfall intensity during the past four decades observed in China. *Sci. Rep.* **2016**, *6*, 38506. [CrossRef]
27. Syafrina, A.H.; Zalina, M.D.; Juneng, L. Historical trend of hourly extreme rainfall in Peninsular Malaysia. *Theor. Appl. Climatol.* **2015**, *120*, 259–285. [CrossRef]

28. Li, J.; Yu, R.C.; Sun, W. Duration and Seasonality of Hourly Extreme Rainfall in the Central Eastern China. *Acta Meteorol. Sin.* **2013**, *27*, 799–807. [CrossRef]
29. Zhao, Y.; Huang, A.; Kan, M.; Dong, X.; Yu, X.; Wu, Y.; Zhang, X.; Cai, S. Characteristics of Hourly Extreme Precipitation along the Yangtze River Basin, China during Warm Season. *Sci. Rep.* **2020**, *10*, 5613. [CrossRef] [PubMed]
30. Ng, C.P.; Zhang, Q.H.; Li, W.H. Changes in Hourly Extreme Precipitation Over Eastern China From 1970 to 2019 Dominated by Synoptic-Scale Precipitation. *Geophys. Res. Lett.* **2021**, *48*, e2020GL090620. [CrossRef]
31. Xiang, Y.; Li, Z.; Wu, Y.; Wang, K.; Yang, J. Spatiotemporal Characteristics of Hourly-Scale Extreme Precipitation in the Sichuan Basin and Its Impact on Normalized Difference Vegetation Index Values. *Atmosphere* **2023**, *14*, 1719. [CrossRef]
32. Zheng, Y.; Xue, M.; Li, B.; Chen, J.; Tao, Z. Spatial characteristics of extreme rainfall over China with hourly through 24-hour accumulation periods based on national-level hourly rain gauge data. *Adv. Atmos. Sci.* **2016**, *33*, 1218–1232. [CrossRef]
33. Zheng, Y.G.; Gong, Y.D.; Chen, J.; Tian, F.Y. Warm-Season Diurnal Variations of Total, Stratiform, Convective, and Extreme Hourly Precipitation over Central and Eastern China. *Adv. Atmos. Sci.* **2019**, *36*, 143–159. [CrossRef]
34. Li, J.; Yu, R.; Yuan, W.; Chen, H. Changes in duration-related characteristics of late summer precipitation over eastern China in the past 40 years. *Climate* **2011**, *24*, 5683–5690. [CrossRef]
35. Bao, X.H.; Zhang, F.Q.; Sun, J.H. Diurnal variations of warm-season precipitation east of the Tibetan Plateau over China. *Mon. Weather Rev.* **2011**, *139*, 2790–2810. [CrossRef]
36. Dai, A.G.; Deser, C. Diurnal and semidiurnal variations in global surface wind and divergence fields. *J. Geophys. Res.* **1999**, *104*, 31109–31125.
37. Chen, Y.R.; Li, Y.Q. Convective Characteristics and Formation Conditions in an Extreme Rainstorm on the Eastern Edge of the Tibetan Plateau. *Atmosphere* **2021**, *12*, 381. [CrossRef]
38. Li, J.; Li, Y.; Zhao, T.; Schiemann, R.; Muetzelfeldt, M.; Jiang, X. Northeastward propagation of nocturnal precipitation over the Sichuan Basin. *Int. J. Climatol.* **2021**, *41*, 2863–2879. [CrossRef]
39. Wu, Y.; Huang, A.; Huang, D.; Chen, F.; Yang, B.; Zhou, Y.; Fang, D.; Zhang, L.; Wen, L. Diurnal variations of summer precipitation over the regions east to Tibetan Plateau. *Clim. Dyn.* **2017**, *51*, 4287–4307. [CrossRef]
40. Yuan, W.; Yu, R.; Zhang, M.; Lin, W.; Chen, H.; Li, J. Regimes of Diurnal Variation of Summer Rainfall over Subtropical East Asia. *J. Clim.* **2012**, *25*, 3307–3320. [CrossRef]
41. Chen, H.; Yu, R.; Li, J.; Yuan, W.; Zhou, T. Why Nocturnal Long-Duration Rainfall Presents an Eastward-Delayed Diurnal Phase of Rainfall down the Yangtze River Valley. *J. Clim.* **2010**, *23*, 905–917. [CrossRef]
42. Carbone, R.E.; Tuttle, J.D. Rainfall occurrence in the U.S. warm season: The diurnal cycle. *J. Clim.* **2008**, *21*, 4132–4146. [CrossRef]
43. Jin, X.; Wu, T.; Li, L. The quasi-stationary feature of nocturnal precipitation in the Sichuan Basin and the role of the Tibetan Plateau. *Clim. Dyn.* **2012**, *41*, 977–994. [CrossRef]
44. Chen, M.C.; Yao, X.P. The characteristics and mechanisms on diurnal variation of summer precipitation over the Tibetan Plateau. *Clim. Dyn.* **2022**, *60*, 2405–2418. [CrossRef]
45. Liu, X.D.; Bai, A.J.; Liu, C.H. Diurnal variations of summertime precipitation over the Tibetan Plateau in relation to orographically-induced regional circulations. *Environ. Res. Lett.* **2009**, *4*, 045203. [CrossRef]
46. Xiao, H.; Chen, J. Numerical study of one plateau vortex moving eastward affecting heavy rainfall in Sichuan. *Plateau Mt. Meteor. Res.* **2010**, *30*, 12–17. (In Chinese)
47. Lin, X.; Randall, D.A.; Fowler, L.D. Diurnal variability of the hydrologic cycle and radiative fluxes: Comparisons between observations and a GCM. *Am. Meteorol. Soc.* **2000**, *13*, 4159–4179. [CrossRef]
48. Xie, Y.F.; Yuan, W.H.; Yu, L.; Hu, X.L. Regional differences in hourly rainfall characteristics over the southeastern extension of the Tibetan Plateau. *Int. J. Climatol.* **2021**, *42*, 1326–1336. [CrossRef]
49. Yuan, W.; Sun, W.; Chen, H.; Yu, R. Topographic effects on spatiotemporal variations of short duration rainfall events in warm season of central north China. *J. Geophys. Res. Atmos.* **2014**, *119*, 19. [CrossRef]
50. Qian, T.T.; Zhao, P.; Zhang, F.Q.; Bao, X.H. Rainy-Season Precipitation over the Sichuan Basin and Adjacent Regions in Southwestern China. *Mon. Weather Rev.* **2015**, *143*, 383–394. [CrossRef]