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Assessment of diurnal variation of summer precipitation over the Qilian Mountains based on an hourly merged dataset from 2008 to 2014

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Abstract: To investigate the diurnal variation of summer precipitation in the Qilian Mountains in the northeast Tibetan Plateau, the hourly precipitation amount for this region during the summers of 2008–2014 are analyzed using an hourly merged precipitation product at 0.1°×0.1° resolution. The main results are as follows. (1) The spatial distribution and temporal variation of mean hourly precipitation amount and frequency are generally similar and hourly precipitations in the eastern and middle portions are larger and more frequent than that in the western portion. The high value area of precipitation intensity is obviously different from that of precipitation amount and frequency. (2) The spatial distribution of daytime precipitation is generally similar to that of nighttime precipitation, and the daytime precipitation is heavier than the nighttime precipitation. (3) The change rate of precipitation has a maximum at 20:00 Beijing time, and a minimum at 12:00. The hourly precipitation amount significantly correlated with frequency, especially for the middle and eastern portions.

Keywords: Qilian Mountains; summer; precipitation; diurnal variation

1 Introduction

The rapid warming trend has been evidenced in the middle-latitude of the Northern Hemisphere, which may result in an acceleration of regional and global water cycles (Ji *et al.*, 2014; IPCC, 2014). The diurnal variation of precipitation is related to the thermal and dynamic processes in the atmosphere, and is attracting increasing attention in global change studies (e.g., Sperber and Yasunari, 2006; Bowen and Fowler, 2015; Wu *et al.*, 2015). It is therefore of great importance to investigate the spatial regime and dynamic mechanism of the diurnal variation of precipitation (Jeong *et al.*, 2011; Folkins *et al.*, 2014; Betts *et al.*, 2013).

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Based on in-situ observations, precipitation has been found to have significant diurnal variations in China (e.g., Li *et al*., 2008; Guo *et al*., 2014; Zhang *et al*., 2014). In southern and northeastern China, precipitation in the summer usually peaks in the late afternoon, but most areas of the Tibetan Plateau have rainfall that peaks at around midnight (Yu *et al*., 2007). Recent studies regarding the diurnal variation of summer rain in China have been reviewed by Yu *et al*. (2014).

The Qilian Mountains are located at the northeast margin of the Tibetan Plateau, and the surrounding areas are much more arid than the mountains (Jia *et al*., 2012). Although the diurnal variation of precipitation is mentioned in a previous nationwide assessment (Zhu *et al*., 2016), detailed information for this region is absent, mostly due to the uneven distribution of the observation network. Satellite data provide a good coverage of high elevations; however, the uncertainty in the satellite-based precipitation data and the short observation period cannot be ignored (Joyce *et al*., 2004; Guo *et al*., 2014). In recent years, a nationwide hourly 0.1°×0.1° precipitation database across China has been released by the National Meteorological Information Center, and measurements using automatic meteorological stations were merged with CMORPH (Climate Precipitation Center Morphing) data (Shen *et al*., 2013, 2014). The merged dataset has been widely used to study the precipitation pattern in China (e.g., Wang *et al*., 2014; Zhou *et al*., 2015; Kang *et al*., 2015; Zhu *et al*., 2016). In this study, we focus on hourly precipitation in the Qilian Mountains, and provide a systemic assessment of diurnal variation of the summer precipitation.

2 Data and methods

2.1 Study area

The Qilian Mountains are located in the northeastern margin of the Tibetan Plateau, where the elevation is generally 4000–5000 m. The Hexi Corridor lies on the northern slope of the Tianshan Mountains, and the Qaidam Basin is on the southern slope (Figure 1). According to the second Chinese Glacier Inventory (Sun *et al*., 2015), existing glaciers in the mountains are 1597.81±70.30 km^2 in area and approximately 84.48 km^3 in volume. During the past

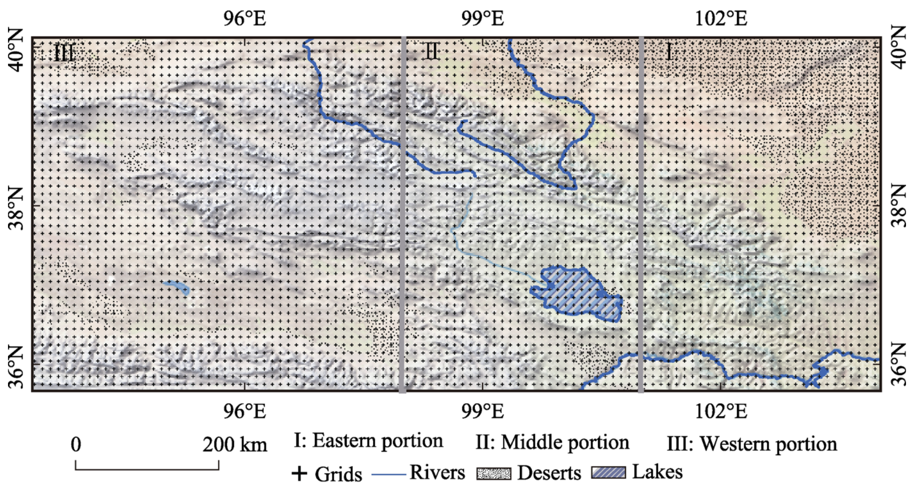

Figure 1 Spatial distribution of grid boxes for hourly precipitation at 0.1°×0.1° resolution in the Qilian Mountains

decades, the glaciers have undergone rapid shrinkage (Wang *et al*., 2011; Tian *et al*., 2010; Chen *et al*., 2015). Owing to various water vapor sources and huge elevation fluctuations, the spatial distribution and seasonal pattern of precipitation are complex in the Qilian Mountains (Jia *et al*., 2008, 2012; Qiang *et al*., 2016). To investigate the spatial diversity, longitudes of 101°E and 98°E were selected as the boundaries of the eastern, middle and western portions of the Qilian Mountains in this study, which was also suggested by Chen *et al*. (2012). As shown in Figure 1, subregions I, II and III are the eastern, middle and western portions of the Qilian Mountains, respectively.

2.2 Data

The hourly merged precipitation data from 2008 to 2014 used in this study were provided by the National Meteorological Information Center (available online at http://data.cma.cn). The nationwide automatic meteorological station data were merged with CMORPH data, and nationwide hourly precipitation with a spatial resolution of 0.1°×0.1° was acquired from 2008 to the present. Details about this product have been described in previous studies (Pan *et al*., 2012; Shen *et al*., 2013, 2014). Owing to the seasonal distribution of precipitation in the study region (Yin *et al*., 2009; Qiang *et al*., 2016), summer (June, July and August) is the season with the most precipitation of the four seasons. In this paper, the focus is on summer precipitation over the Qilian Mountains during 2008–2014.

2.3 Methods

The precipitation amounts for each hour were processed to give hourly mean series over 24 hours (usually on a monthly basis). The precipitation frequency describes the existence of rainfall within a specific period, and is a dimensionless parameter. The precipitation intensity is the mean value of the hourly precipitation amount during rainfall hours. To study the difference in precipitation amount between daytime and nighttime, they are defined as periods from 08:00 to 20:00 (Beijing time) and from 20:00 to 08:00, respectively. To assess the variation of hourly precipitation, the precipitation change rate is also applied in this paper, and can be calculated as:

$$P = \frac{\frac{1}{n}\sum_{i=1}^{n}|x_i - \overline{x}|}{\overline{x}} \times 100\% \quad i=1, 2, 3..., n (1)$$

where x_i is the hourly precipitation amount in mm/h, $\overline{x}$ is the mean hourly precipitation amount in mm/h, i is the hour of the precipitation and the n is the total hour of the precipitation.

Pearson's correlation coefficient (r) and two-tailed t tests were used to assess linear correlation and statistical significance.

3 Results and analysis

3.1 Hourly precipitation amount

The diurnal variation of mean hourly precipitation amount during the summers of 2008–2014 is shown in Figure 2. It is clear that the precipitation amount in the eastern and middle portions is much larger than that in the western portion, which is consistent with previous studies using interpolated grid products (e.g., Qiang *et al*., 2016) and in-situ measurements (e.g., Jia, 2012) for this region. On a monthly basis, the maximum is usually seen for the July series, especially for the eastern and middle portions. In the middle portion, the peak time for both the July and summer series is 18:00 Beijing time, while for June and August it is 17:00 and 20:00, respectively. Generally, the precipitation peak time is between 17:00 and 20:00, which means that the rainfall is usually concentrated in the evening.

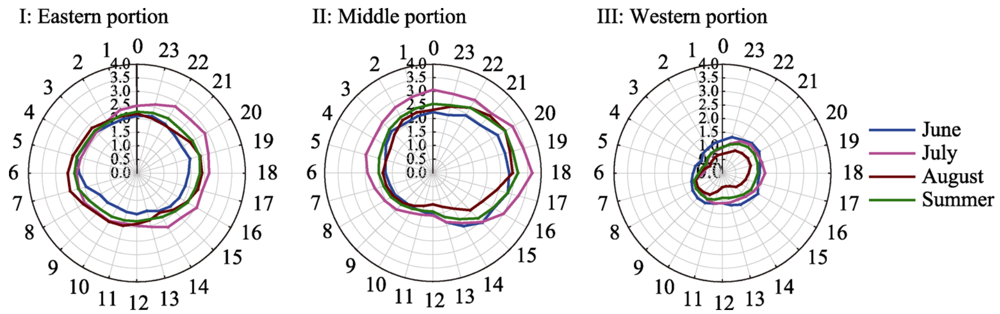

Figure 2 Mean hourly precipitation amount in mm/month for each subregion in the Qilian Mountains during the summers of 2008–2014

The spatial distribution of the mean hourly precipitation amounts in the Qilian Mountains is shown in Figure 3, with the eastern and middle portions displaying larger precipitation amounts. From 08:00 to 12:00, the precipitation amount generally declines for the whole region. After 12:00, the hourly precipitation amount increases significantly. It should be mentioned that the precipitation amount on the northern slope is larger than that on the southern slope for these hours. There is a significant decreasing trend of the amount from 22:00 to 07:00, and then the amount on the southern slope is larger than that on the northern slope. In addition, the precipitation is mainly concentrated in the hours from 17:00 to 21:00.

3.2 Hourly precipitation frequency

As shown in Figure 4, the hourly precipitation frequency in the eastern and middle portions is larger than that in the western portion. For the eastern and middle portions, the month with the maximum precipitation frequency is July, and for the western portion, June shows the maximum frequency. In the middle portion, the peak time of precipitation frequency for the June series is 17:00 and the peak time for the July and August series is 21:00 and 18:00, respectively. The precipitation frequency peak time of the Qilian Mountains is generally consistent with the above-mentioned mean hourly precipitation. The spatial distribution of precipitation frequency in the Qilian Mountains is shown in Figure 5. In addition, the precipitation frequency of the mountains is larger than that of the surrounding areas, indicating the importance of high elevation in the regional water cycle.

3.3 Hourly precipitation intensity

Figure 6 demonstrates that the diurnal variation of precipitation intensity is different from that of the hourly precipitation amount and frequency, and the precipitation intensity is generally similar for each subregion of the Qilian Mountains. In the western portion, the precipitation intensity peak time in June is 23:00–00:00; in contrast, the peak times in July are

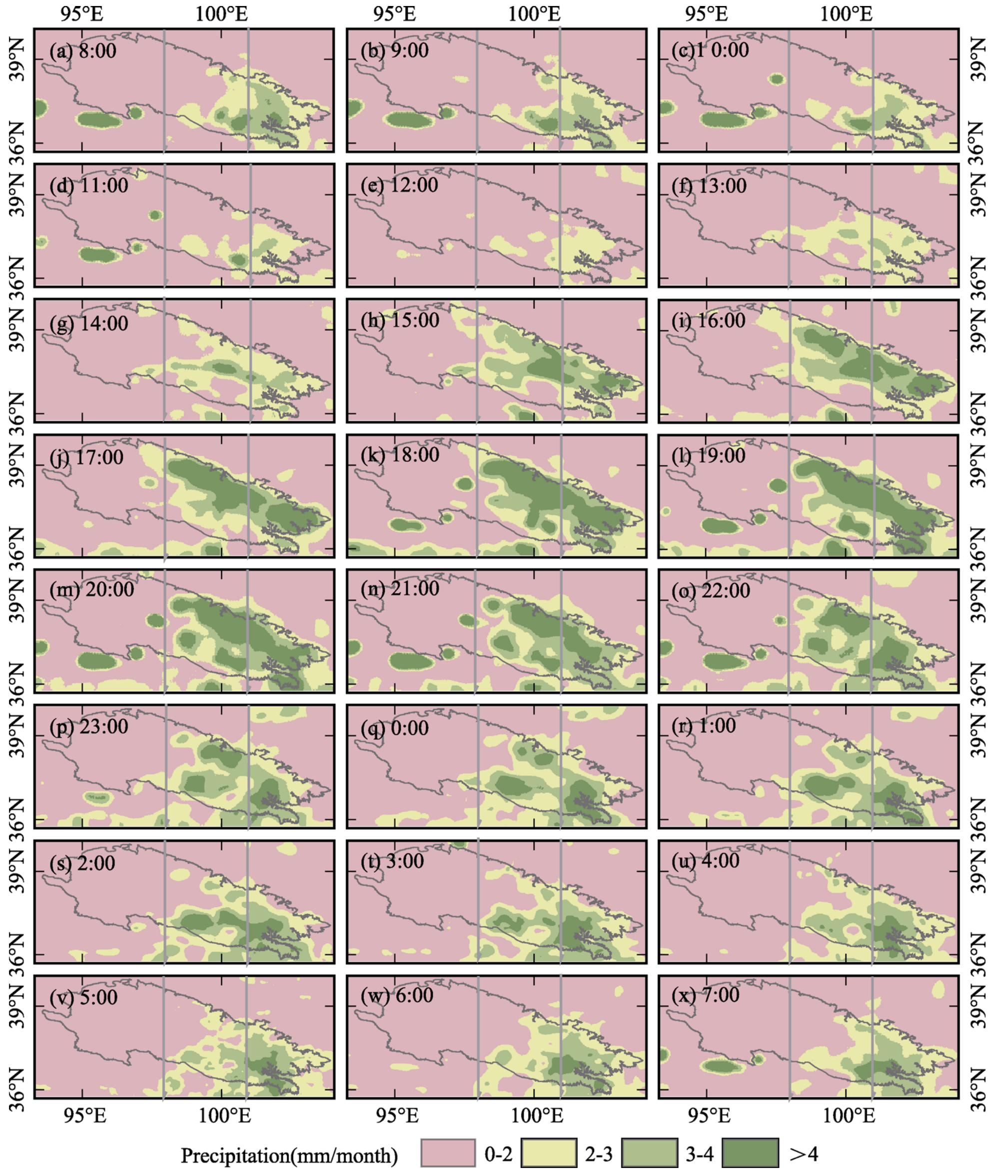

Figure 3 Spatial distribution of mean hourly precipitation amount in mm/month for each hour in the Qilian Mountains during the summers of 2008–2014

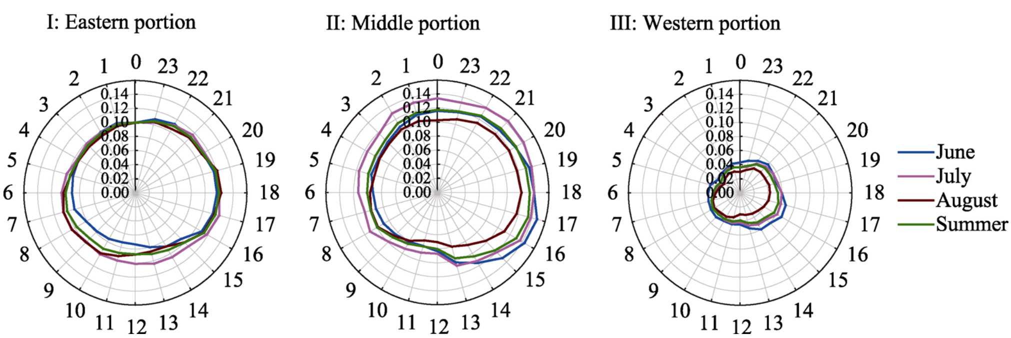

Figure 4 Mean hourly precipitation frequency for each subregion in the Qilian Mountains during the summers of 2008–2014

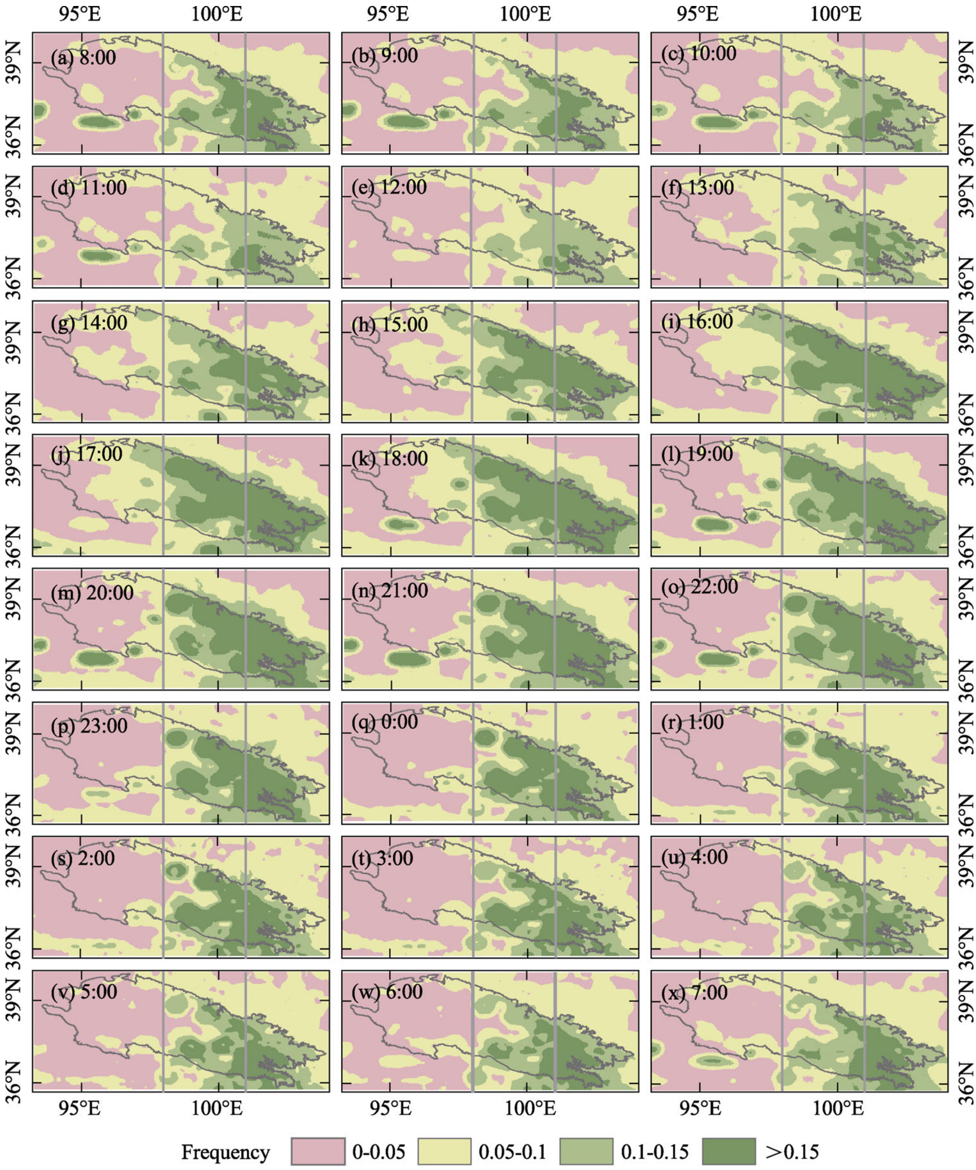

Figure 5 Spatial distribution of mean hourly precipitation frequency for each hour in the Qilian Mountains during the summers of 2008–2014

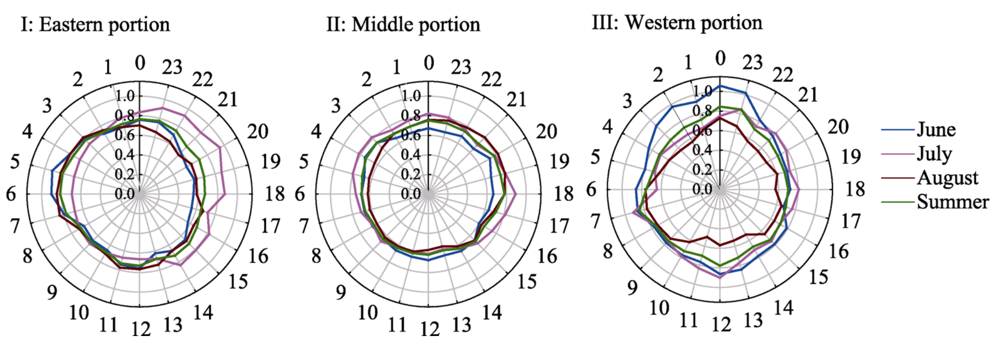

Figure 6 Mean hourly precipitation intensity in mm/h for each subregion in the Qilian Mountains during the summers of 2008–2014

12:00 and 07:00, while the time in August is 06:00–07:00. The spatial distribution of precipitation intensity is exhibited in Figure 7. The high value area of precipitation intensity is very different from that of the precipitation amount and frequency. There is no good correlation of precipitation intensity with elevation.

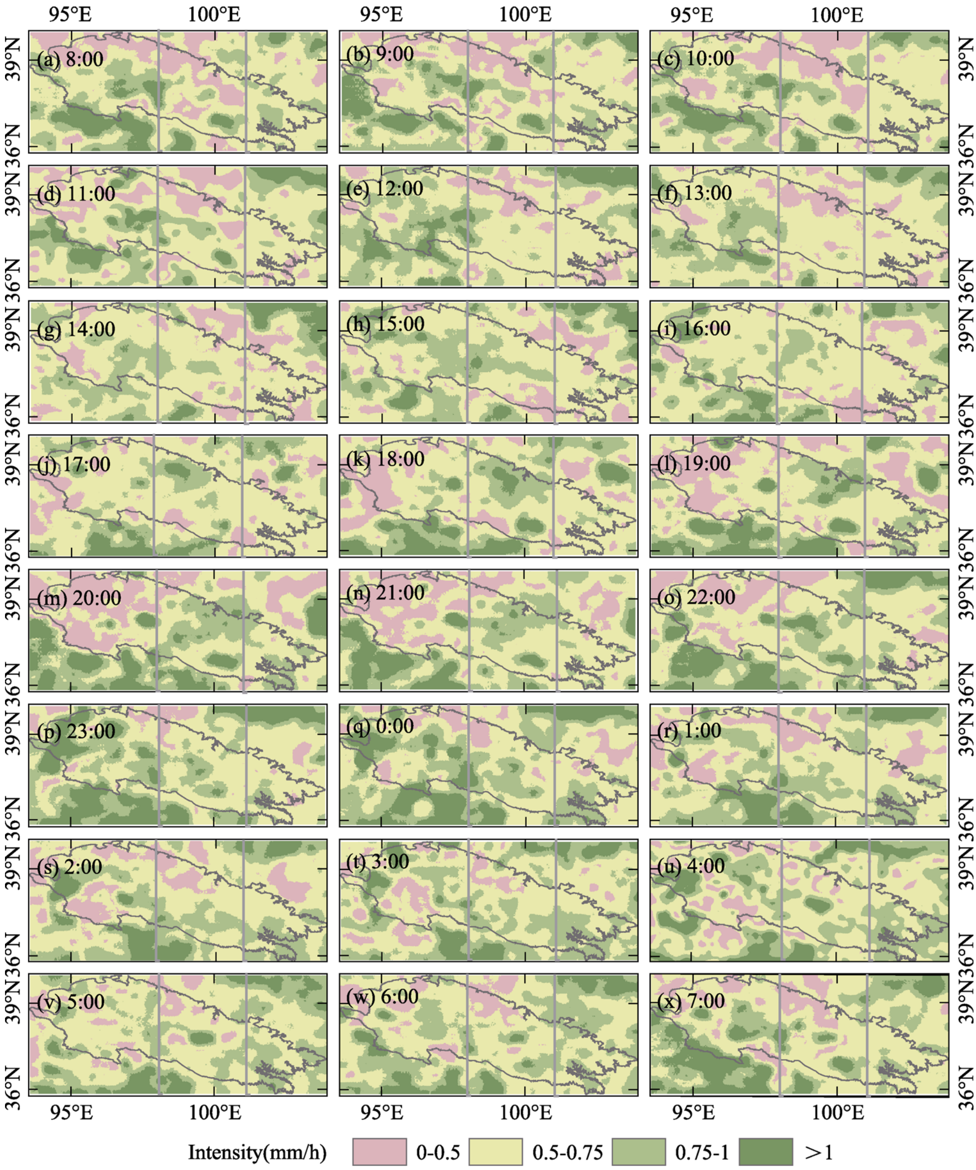

Figure 7 Spatial distribution of mean hourly precipitation intensity in mm/h for each hour in the Qilian Mountains during the summers of 2008–2014

3.4 Daytime and nighttime precipitation

Figure 8 shows that the spatial distribution of daytime precipitation is generally similar to that of the nighttime, and the precipitation in the eastern and middle portions is heavier than that in the western portion. As shown in Figure 9, there is an increasing trend in both daytime and nighttime precipitation amounts. In the first four years, precipitation during the

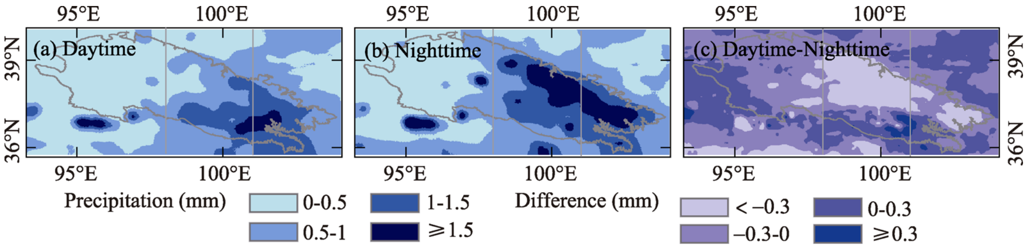

Figure 8 Spatial distribution of precipitation in daytime (a), nighttime (b) and their difference (c) in mm/day for each subregion in the Qilian Mountains during the summers of 2008–2014

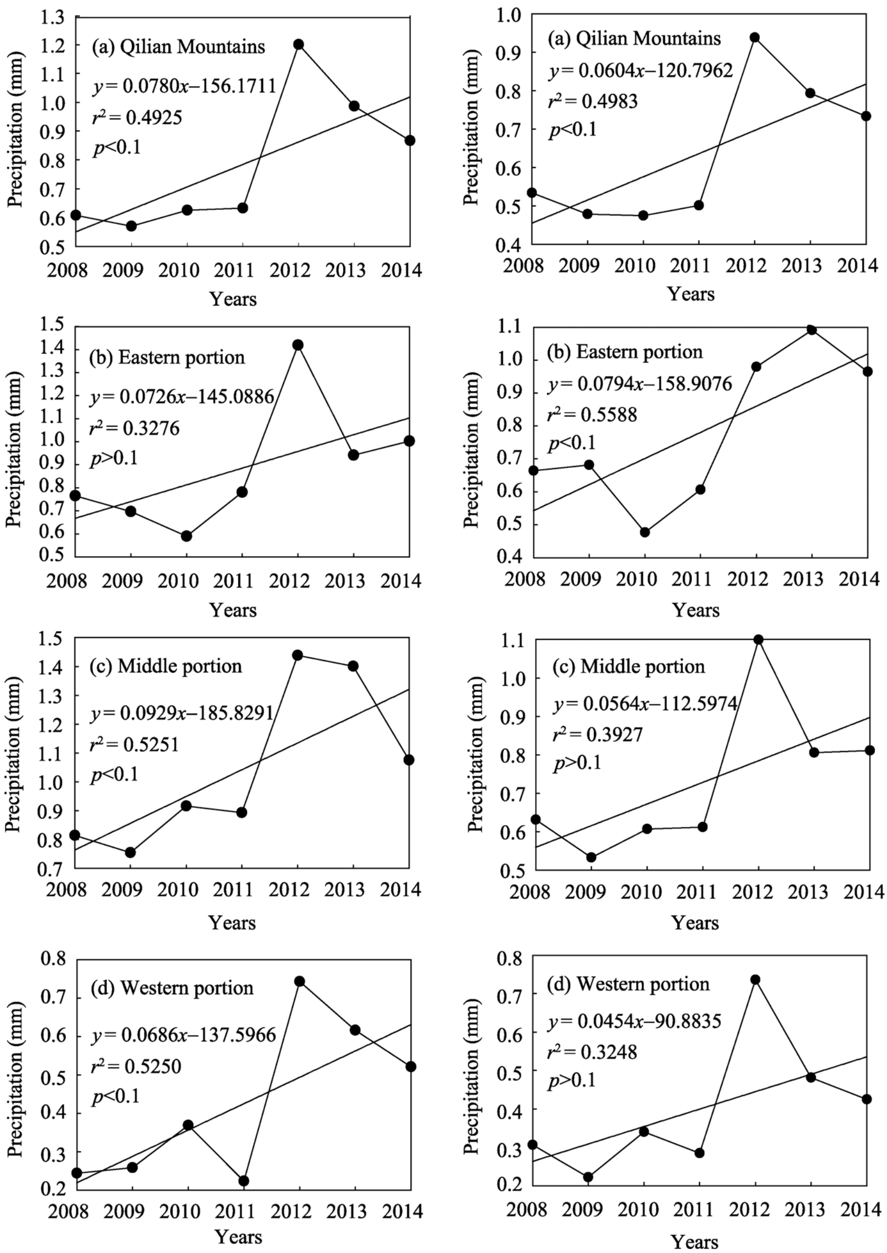

Figure 9 Inter-annual change of daytime and nighttime precipitation in mm per day in the Qilian Mountains during the summers of 2008–2014

daytime and nighttime was generally stable, and the fluctuation of precipitation amount was very limited. However, the precipitation peaked in 2012 for the entire study region. After 2012, the precipitation amount decreased to some degree. A similar inter-annual trend can be detected in each subregion, but detailed differences still exist.

3.5 Change rate and correlation coefficient

The changes in rates of precipitation in the Qilian Mountains during the summers of 2008–2014 are shown in Figure 10. The changes in rates in all the subregions vary between 5% and 38%, with a maximum at 20:00 in the middle and western portions, while in the eastern portion, the maximum value is seen at 19:00. When the change rate of precipitation is high, extreme weather events and disasters may occur frequently (Fu, 2013). The minimum value of change rate is found at 12:00, which is consistent across the three subregions. The correlation analysis results in the different subregions are shown in Table 1. The correlation between precipitation amount and frequency is the strongest among these parameters. All the coefficients between the precipitation amount and frequency are statistically significant, especially for the eastern and middle portions in the Qilian Mountains.

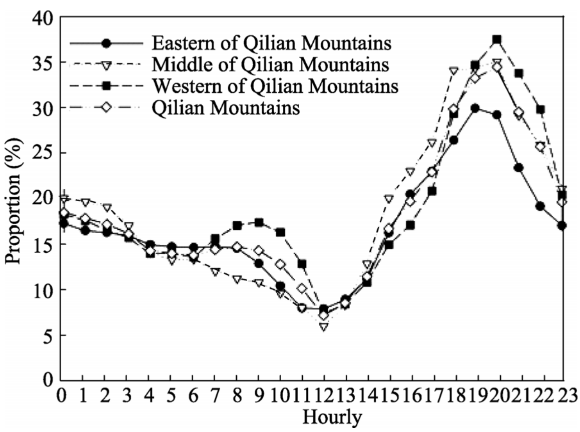

Figure 10 Hourly variation of precipitation change rate in the Qilian Mountains during the summers of 2008–2014

Table 1 Correlation coefficients of the mean hourly precipitation amount, frequency and intensity in the Qilian Mountains during the summers of 2008–2014

	Eastern portion	Middle portion	Western portion	Qilian Mountains
r(amount vs. Intensity)	0.366	0.887**	–0.062	0.194
r(amount vs. frequency)	0.834**	0.963**	0.598**	0.931**
r(intensity vs. frequency)	–0.036	0.806**	–0.483*	–0.071

Note: *Statistically significant at the 0.01 level. ** Statistically significant at the 0.05 level.

4 Conclusions

Based on an hourly merged precipitation product at 0.1°×0.1° resolution, the mean hourly precipitation amount, frequency and intensity in the Qilian Mountains during the summers of 2008–2014 have been analyzed. The main conclusions are as follows.

The diurnal variation of the mean hourly precipitation amount is consistent with that of precipitation frequency, and the amount and frequency in the eastern portion are larger than those in the western portion. The high value area of precipitation intensity is obviously different from that of the precipitation amount and frequency.

The spatial distribution of daytime precipitation is generally similar to that of nighttime precipitation. The daytime precipitation is generally heavier than that of the nighttime precipitation. During 2008–2014, the daytime and nighttime precipitation series increased, with a peak in 2012.

The change rate of precipitation in the study region has a maximum at 20:00 Beijing time, and a minimum at 12:00. The linear correlation between the precipitation amount and frequency is strong, especially in the eastern and middle portions.

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