Spatial Distribution of Diurnal Rainfall Variation in Summer over China

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ABSTRACT

Diurnal rainfall variation plays an important role in the characterization of regional climate. Most existing research used predefined region boundaries to study the spatial differences of diurnal rainfall variation, which depends on experiential knowledge and is somewhat subjective. In this study, the k-means clustering algorithm was used to mine the spatial distribution of diurnal rainfall variation from gridded precipitation data over China. First, clustering was conducted according to the hourly rainfall frequency at each grid cell. A cluster number large enough to find the main types of diurnal rainfall variation was used. Then similar clusters were merged according to the peak time and amplitude of the diurnal rainfall variation. Each merged cluster corresponds to one type of diurnal variation, and the locations of grid cells in each merged cluster form the spatial distribution. Thus, the classification maps of diurnal rainfall variation can be obtained. From the spatial distribution maps, the conclusions of existing research (e.g., the distribution of well-known nocturnal rainfall in southwestern China, the prevailing afternoon rainfall regions) were confirmed. Some new findings were found, such as the spatial patterns of nocturnal rainfall regions along slopes of the macroterrain and the different types of diurnal rainfall variation in the North China Plain. The diurnal rainfall variation in some regions also shows a close relationship with land cover. The results of this study can provide valuable information for further mechanism studies, and the proposed approach can serve as a useful tool for studies on diurnal rainfall variation in other regions.

1. Introduction

Diurnal rainfall variation plays an important role in the characterization of regional climate. It can help to detect weather and climate extremes, provide valuable clues for mechanism studies of local rain formation, and can also be used as a powerful tool to verify numerical forecast models (Trenberth et al. 2003; Lu et al. 2015, 2017; Ryu et al. 2016). As it is driven by solar radiation and affected by factors such as a heterogeneous underlying surface, multiscale atmospheric circulations, and water vapor path, diurnal rainfall variation shows remarkable regional differences (Carbone et al. 2002; Levizzani et al. 2010; Bao et al. 2011; Chen et al. 2015).
Existing studies usually adopted a top-down approach to studying the regional differences of diurnal rainfall variation, which needs predefined region boundaries. These region boundaries were often defined by natural geographic districts or just by rectangles (Jin et al. 2013; Wilson and Barros 2015; Yu et al. 2007a; Singh and Nakamura 2010). For example, in the former case, Jin et al. (CMORPH) precipitation data with hourly observation (NOAA) Climate Prediction Center morphing technique National Oceanic and Atmospheric Administration China and is dated from 2008 to 2015. It combined the product from the China Meteorological Administration (CMA) was used in this study. This dataset covered regions over China, and Singh and Nakamura (2010) studied the diurnal rainfall variation in two rectangular regions over central India and the southern Himalayan foothills.

The process of defining region boundaries depends on experiential knowledge and is somewhat subjective. In recent years, with the abundance of site-observed and satellite-based precipitation data, spatially continuous gridded precipitation fields can be obtained (Xie and Xiong 2011; Yong et al. 2016), which makes it possible to use a bottom-up approach to divide regions for the study of diurnal rainfall variation. By using the bottom-up approach, basic spatial units (e.g., grid cells in this study) can be divided into different groups according to their characteristics of diurnal rainfall variation. The spatial units within each group have similar diurnal rainfall variation, and their extents form the spatial distribution for one type of diurnal variation. In this way, the spatial distribution of diurnal rainfall variation can be objectively determined by gridded precipitation data, which is useful in analyzing and understanding the drivers of local rainfall formation.

In this research, the summer (June–August) rainfall over China, which accounts for 50%–80% of the total annual rainfall (Turner and Annamalai 2012; Dong et al. 2016), was chosen to conduct the case study. The k-means clustering algorithm was used to mine the spatial distribution of diurnal rainfall variation from gridded precipitation data. The characteristics of each type of diurnal variation were analyzed and compared with existing studies.

2. Data and methodology

An hourly 0.1° × 0.1° resolution gridded precipitation product from the China Meteorological Administration (CMA) was used in this study. This dataset covered China and is dated from 2008 to 2015. It combined the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center morphing technique (CMORPH) precipitation data with hourly observation precipitation data from more than 30 000 automatic meteorological stations over China (Pan et al. 2012). Shen et al. (2014) evaluated the accuracy of this dataset, and the results showed that it can capture hourly rainfall variation over China quite well.

Rainfall frequency, affected little by weather conditions, is one of the main parameters that can be used to describe rainfall. In the present study, the hourly rainfall frequency was used to present the diurnal rainfall variation, which was a 24-dimensional vector corresponding to 24 h in a day and was calculated as the times of measurable precipitation (i.e., ≥0.1 mm h⁻¹) divided by the times of total observations for each hour (Zhou et al. 2008). Then, the 24-dimensional vector of rainfall frequency was normalized by using the following formula (Yu et al. 2007b):

\[
D_a(h) = \left[ \frac{R_a(h)}{\frac{1}{24} \sum_{i=1}^{24} R_a(i)} \right] - 1 .
\]

Here, \(D_a(h)\) represents the normalized rainfall frequency at time \(h\), and \(R_a(h)\) represents the original rainfall frequency at time \(h\).

Local solar time (LST) was used to calculate the hourly rainfall frequency at each grid cell, which was obtained from UTC time using the following formula:

\[
\text{LST} = \text{UTC} + \text{Lon}/15 ,
\]

where LST represents the local solar time for each grid cell, UTC represents the universal coordinated time, and “Lon” is the longitude.

The k-means clustering algorithm was adopted to divide grid cells over China into different clusters based on the 24-dimensional vector of the normalized hourly mean rainfall frequency at each cell. In general, the k-means clustering algorithm aims to partition \(n\) observations into \(k\) clusters according to the rule that each observation belongs to the cluster with the nearest distance in Euclidean space. More details of this algorithm can be found in Rajaraman and Ullman (2011).

For the k-means clustering algorithm, the number of clusters \(k\) needs to be determined in advance. In the present study, various cluster numbers \(k\) ranging from 2 to 30 were tried. The average distance from a point to its corresponding cluster center in the attribute space was calculated. These distances with different cluster numbers formed a curve (Fig. 1). In this curve, the average distance decreased with the increase of the cluster number, but the drops in distance declined (i.e., the curve became flatter). For example, when the cluster number was 19, the average distance was only 0.008
smaller than that of 18 clusters. A very small drop in the average distance means the cluster number was larger than the “true” number of clusters (Rajaraman and Ullman 2011). So in this study, the cluster number of 19 was thought to be large enough to figure out the main types of diurnal rainfall variation, and the results of 19 clusters were used in the following studies.

The problem brought by a large cluster number was that it would lead to some similar clusters, which should be merged. Peak time is the primary information of diurnal rainfall variation. If we are only interested in peak time, clusters with similar peak times, whether with similar or different amplitudes, should be classified as one type of diurnal variation. The peak times were deemed to be similar if they fell into the same period of the following six time periods (based on LST): early morning (0200–0600 LST), morning (0600–1000 LST), midday (1000–1400 LST), afternoon (1400–1800 LST), evening (1800–2200 LST), and midnight (2200–0200 LST) (Yuan et al. 2012). For multipeak diurnal rainfall variation, two clusters can be merged only if all their peak times are similar. After merging, the locations of grid cells within each merged cluster form the spatial distribution of one type of diurnal rainfall variation. Thus, a peak time map for diurnal rainfall variation can be obtained.

Besides peak time, peak amplitude can also be considered in the abovementioned cluster merging process. In this case, two clusters can be merged only when both their peak times and corresponding amplitudes are similar. The criterion to judge the similarity of peak times has been described above. The peak amplitudes were deemed to be similar if the normalized rainfall frequency of the peak fell into the same range of the following: less than 0.4, more than 0.4 but less than 0.8, and more than 0.8. In this way, the spatial distribution of diurnal rainfall variation can be obtained considering both peak times and their amplitudes.

3. Results

Two spatial distribution maps of diurnal rainfall variation in summer over China were obtained (Figs. 2, 3). Figure 2 shows the map of diurnal rainfall variation classified by peak time over China, and there are eight types of regions with distinct peak times. Considering the peak amplitude of diurnal rainfall variation, subregions in regions I and IV emerged (Fig. 3).

As Fig. 1 shows, region I is the largest area among eight types of diurnal rainfall variation. This region covers most of China and accounts for 58.44% of China’s total land area. Region I was divided into three subregions in Fig. 3: I-1, I-2, and I-3, which have peak amplitudes of less than 0.4, less than 0.8 but larger than 0.4, and larger than 0.8, respectively. These prevailing afternoon rainfall regions were mainly distributed in three areas: most of southern China, the middle of the Tibetan Plateau (TP), and northeastern China (region I in Figs. 2 and 3). In southern China, the amplitude of afternoon rainfall peaks decreased from south to north. In the TP region, the largest amplitudes occurred in the middle region, while northeast China was dominated by subtype I-2 with moderate amplitudes (Fig. 3).

Regions II, III, and IV are mainly distributed in or around mountainous regions. They are usually adjacently located from west to east with one region followed by another. The time of the rainfall peak for these three regions shows an eastward delay from region II to region III and then to region IV; the time of the rainfall peak is evening in region II (1900 LST), midnight in region III (2400 LST), and early morning in region IV (0500 LST).
Similar to region I, region IV was also divided into two subregions considering the peak amplitude of diurnal rainfall variation: regions IV-1 and IV-2. The peak amplitude in region IV-1 is slightly larger than 0.4 (i.e., 0.41), and that in region IV-2 is less than 0.4 (i.e., 0.14). Region IV-1 is mainly distributed in the west, while region IV-2 is in the east. The other regions in Fig. 2 do not have subregions and are not shown in Fig. 3.

Compared with previous studies, the well-known regions with prevailing nocturnal rainfall were identified, including east of the Yanshan and Taihang Mountains area (area A in Fig. 4; He and Zhang 2010; Bao and Zhang 2013), the eastern periphery of the TP, and the adjacent western Sichuan Basin (area B; Yeh and Gao 1979; Yu et al. 2007a), and the Yarlung Tsangpo Canyon in the south of the TP (area G). In area A, the region with early night rainfall peaks spreads along the Yanshan and Taihang Mountains, and the region with midnight rainfall peaks is located in plains to the east of the these mountains. In area B, the region with early night rainfall peaks is distributed at the eastern edge of the TP, the region with midnight rainfall peaks is distributed along the slope of the eastern TP to the west of the Sichuan Basin, and the prevailing early morning rainfall mainly occurs in the middle of the Sichuan Basin. In the Yarlung Tsangpo Canyon (area G), rainfall peaks at early night and midnight dominate.

Except for the well-known prevailing nocturnal rainfall regions mentioned above, prevailing nocturnal rainfall was also found in some other regions that were less studied before, such as the south slope of the TP (area C), the southwest of the Junggar Basin (area D) and the west of the Tarim Basin (area E), and the canyon area in the west of the TP (area F). In addition, region V,
with a midday rainfall peak (1200 LST), was also not mentioned by previous studies. This type of diurnal rainfall variation is scattered in southwestern and northwestern China.

Regions VI and VII show an obvious two-peak diurnal variation and are mainly distributed in the northwest of China. The two peaks of region VI appear in the morning (0800 LST) and the evening (1900 LST), and those of region VII appear at midday (1200 LST) and midnight (2400 LST). The difference is that region VI consists of some small patches, while region VII consists of several broad and continuous areas.

In addition, region VIII, without any obvious peaks in diurnal rainfall variation, is mainly spread between the afternoon peak rainfall region (i.e., region I) and the nocturnal peak rainfall regions (i.e., regions II, III, and IV).

4. Discussion

Diurnal rainfall variation is driven by solar radiation and affected by factors such as a heterogeneous underlying surface, multiscale atmospheric circulations, and water vapor path. The mechanism of diurnal rainfall variation is very complicated. For example, Chen et al. (2015, 2017) pointed out that the low-level convergence by land/sea in southern China was the main reason for the prevailing nocturnal rainfall on the windward slope of the mountainous area in the Pearl River Delta (PRD) region. But over large-scale mountains and adjacent plains or basins in the west and north of China, many researchers also pointed out that propagation of the diurnal rainfall peak from late afternoon to night is strongly associated with the thermally driven regional mountain–plains solenoid (MPS) circulation (He and Zhang 2010; Jin et al. 2013; Sun and Zhang 2012; Bao and Zhang 2013; Zhang et al. 2014).

The goal of the present study is to detect the spatial distribution of diurnal rainfall variation in summer over China. Although the detailed spatial distribution of diurnal rainfall variation was given (Figs. 2 and 3), the mechanism study for each type of diurnal rainfall variation over China is a huge topic and beyond the scope of this study. Therefore, in the following we just
discuss some types of diurnal rainfall variation at large scales.

a. Spatial distribution of prevailing nocturnal rainfall

The diurnal rainfall variation maps provided a new perspective to detect the relation between the terrain and prevailing rainfall. Figure 5 shows seven elevation profiles from area A to area G. The corresponding section lines for these profiles are shown as green solid lines (lying in regions with afternoon rainfall peaks) and yellow dashed lines (lying in regions with nocturnal rainfall peaks) in Fig. 4. The four background colors in Fig. 5 present rainfall peaks in the afternoon, early night, midnight, and early morning, respectively.

As shown in Fig. 5, the prevailing nocturnal rainfall regions are distributed in the canyon areas (profiles f and g) as well as in the slopes of the macroterrain and their adjacent plains (profiles a–e). There is an obvious spatial arrangement following the macroscale terrain. Along the slope of the macroterrain, the peak times of nocturnal rainfall regions show a time-delay propagation from the mountains to plains. The regions with rainfall peaks in the afternoon are distributed on the top or upslope of the mountains, the regions with early night rainfall peaks are mainly distributed on the downslope of the mountains, and most regions with early morning rainfall peaks are located in the plains adjacent to the mountains. Additionally, the regions with midnight rainfall peaks are mainly located between the regions with early night rainfall peaks and those with early morning rainfall peaks. While in the canyon areas, as the profiles f and g show in Fig. 5, nocturnal rainfall regions are distributed in the canyon and are surrounded by the regions with afternoon rainfall peaks on the top of the mountains.
The spatial pattern of the prevailing nocturnal rainfall regions mentioned above can be explained by the propagation of the rain belt driven by the MPS circulation (Jin et al. 2013; Bao and Zhang 2013). During daytime, the land surface is warmed by solar radiation shortly after sunrise, and the near-surface atmosphere is warmed by the land surface. At the same altitude, the atmosphere over the top and upslope of the mountains is closer to the land surface than that over the valleys or plains. Therefore, the atmosphere over the top and upslope of the mountains often warms faster. The differentially stronger surface heating on the mountains than in the valleys results in the near-surface flow blowing from valleys to mountaintops (shown as Fig. 6a). The updraft of warm and moist air over the top and upslope of the mountains triggers the prevailing rainfall in the afternoon.

After sunset, the land surface cools down substantially because of the radiation cooling effect, which then cools down the near-surface atmosphere. At the same altitude, the atmosphere over the top and upslope of the mountains cools down faster than that over the valleys or plains because of the closer distance to the land surface. The cold air mass over the mountains begins to sink and flows along the slope of the mountains to the plains (canyons can also be regarded as plains). At the same time, the relatively warmer and moister air in the downslope of the mountains and the plains is lifted up by the cold downdraft. The circulation transitions to the inverse phase compared with the circulation in the daytime, where the downdraft of the MPS circulation appears on the top of the mountains, and the updraft begins to dominate over the plains (shown as Fig. 6b). The upward branch of the MPS circulation at the downslope of the mountains or the plains causes atmospheric instability and leads to the prevailing nocturnal rainfall (Zhang et al. 2014). As the flow propagates from mountaintop to plains driven by wind, the nocturnal rain belt moves accordingly, which results in the time-delay pattern of rainfall peaks along the slope of the macroterrain. The wind field analysis in existing research is consistent with our analysis. For example, according to numerical experiments using the Weather Research and Forecasting (WRF) Model, Bao and Zhang (2013) pointed out that the wind direction at night in region A is mainly downslope (i.e., southeastward). Jin et al. (2013)
also found the wind direction at night in region B is downslope (i.e., northeastward) using the ERA-Interim reanalysis data provided by European Centre for Medium-Range Weather Forecasts (ECMWF).

b. Spatial distribution of prevailing afternoon rainfall

The mechanism for the late afternoon maximum rainfall can be explained by surface solar heating, which has been well studied by previous researchers (Yuan et al. 2012; Chen et al. 2015; Li et al. 2017). Previous studies have pointed out that solar heating causes the maximum low-level atmospheric instability in the afternoon, which results in moist convection and short-duration rainfall.

However, the amplitude of diurnal rainfall variation has been seldom studied. In this study, the subregion map considering the peak amplitude of diurnal rainfall was first presented (Fig. 3). As shown in Fig. 3, the amplitude of the afternoon rainfall peak in southern China seems related to the distance to the South China Sea. Some previous research pointed out that the formation of the diurnal rainfall variation in southern China is under the control of the sea–land wind (Yu et al. 2014; Chen et al. 2017). Chen et al. (2015) also suggested that the ambient onshore wind speed (land breeze and sea breeze) is the key factor that controls the intensity and diurnal variation of the coastal rainfall over southern China during summer. During the daytime, the land surface is usually warmer than the sea surface. As forced by the thermal contrast between the land and sea, the large-scale sea–land wind moves from the sea to inland and reaches its peak at 1400 LST. In this process, the moist air is first lifted by the continuous mountains along the coast, which gives rise to the first rainfall. As the sea–land wind moves farther inland, air moisture decreases gradually, and the prevailing afternoon rainfall will also decrease. Therefore, the peak amplitude of the prevailing afternoon rainfall in southern China shows a decreasing trend from the coast to inland.

In addition, it is also found that terrain can affect the amplitude of diurnal rainfall variation. Figure 7 illustrates the digital elevation model (DEM) and subregions with afternoon rainfall peaks in southern China. Six mountains, namely, the Qinling, Dabashan, Wushan, Dabieshan, Jiuling, and Yellow Mountains, are shown as the black solid lines in Fig. 7. It can be found that the peak amplitude of diurnal rainfall variation in mountain areas is larger than that in their surrounding plains. This conclusion still holds true in the other regions with afternoon rainfall peaks (Fig. 3). This proves that terrain can not only affect the phase of diurnal rainfall variation, but also affect its amplitude.

c. Spatial distribution of diurnal rainfall variation with double peaks

Previous studies have pointed out that land cover plays significant roles in the formation of diurnal rainfall variation due to the complexity of Earth–atmosphere interactions (Ramos da Silva et al. 2011; Wang et al. 2012; Guo et al. 2014). Figure 8 shows the land cover for region VI in northwestern China. It can be found that
patches 1, 2, and 3 with type VI are located in big lakes (Fig. 8a); the only patch of type VI in northeast China is also located in the largest lake of this region, Hulun Lake (Fig. 2). Patches 4 and 5 are located at the top of the Tianshan Mountains. Figure 8b shows this area's color-composite image of 8-day MODIS products from 4 to 12 July 2015, the hottest season in northwestern China. The white pixels represent ice and snow, the green pixels represent vegetation, and the gray pixels represent bare land and desert areas. It can be seen that patches 4 and 5 (in the red solid circle areas) are covered by ice or snow. Actually, the top of the Tianshan Mountains is covered by a glacier year-round. In summer, some of the ice and snow will melt and result in a moist condition in these areas. Therefore, it can be inferred that region VI is likely related to the moist underlying surface conditions in dry regions.

On the contrary, the underlying surface of region VII is mostly desert. For example, the largest desert, the Taklimakan Desert, and the second largest desert, the Gurbantunggut Desert, are in this region. The diurnal rainfall variation in this region has two rainfall peaks, one at midday and the other one at midnight. The midday peak can be explained by the surface solar heat.
heating at noon. As for the midnight rainfall peak, Ma and Wang (2013) pointed out that mesoscale convective systems have a nocturnal occurrence at Taklimakan Desert, which may be the reason for the prevailing nocturnal rainfall.

It should be noted that detailed mechanisms related to these types of diurnal rainfall variation are complicated. For example, it is still not clear why diurnal rainfall variation of type VI was not found over some of the largest freshwater lakes in southeastern China. Detailed mechanisms are beyond the scope of this study, but the spatial distribution of diurnal rainfall variation obtained in this research can provide valuable spatial information for further studies on this question.

d. Diurnal variation rainfall in the North China Plain

Compared with previous studies, more details about the spatial distribution of diurnal rainfall variation emerged in the North China Plain (area A and the plain in the south in Fig. 4). In previous studies, Yu et al. (2007a) found two comparable diurnal rainfall peaks over this area in summer, one in the early morning and the other one in the afternoon. In our study, five types of diurnal rainfall variations were found, which are regions II and III (these two regions can be seen clearly in Fig. 4) and regions IV-2, I, and VIII (these three regions can be seen in Fig. 2). The prevailing afternoon and night rainfall in the north of the North China Plain were also noted from the statistical analysis of long-term radar observations in recent studies (Chen et al. 2012, 2014). The shapes of these regions are irregular, so the subjectively defined rectangles in previous studies cannot depict their spatial distribution. These findings show the advantages of the bottom-up approach used in this study.

e. Diurnal variation of rainfall frequency, rainfall amount, and rainfall intensity

With the help of the objective spatial distribution of diurnal rainfall variation, we can also detect the relationships among the diurnal variation of rainfall frequency, rainfall amount, and rainfall intensity at the regional scale. The intensity and the amount of diurnal rainfall were also normalized using Eq. (1).

Figure 9 shows the diurnal variation of rainfall intensity, rainfall amount, and rainfall frequency for regions I-2, III, V, and VII in Figs. 2 and 3. As shown in Fig. 9, the diurnal variation of rainfall amount is consistent with that of rainfall frequency. But the diurnal variation of rainfall intensity is dissimilar with that of rainfall frequency and rainfall amount. The amplitudes of diurnal variation for rainfall intensity are much smaller than those of rainfall frequency and rainfall amount. We did the same comparison for the other regions, and this holds true for all the regions.

5. Concluding remarks

This study used a clustering algorithm to mine the spatial distribution of diurnal rainfall variation from
gridded precipitation data over China, and maps of diurnal rainfall variations considering peak time as well as the corresponding amplitude were obtained. Compared with previous studies, this approach avoided the subjective definition of study boundaries that depend on experiential knowledge, and the obtained results were more objective and comprehensive. Our study confirmed the conclusions of existing research (e.g., the well-known nocturnal rainfall in southwestern China), and some new findings were found, such as the spatial patterns of nocturnal rainfall regions along slopes of the macroterrain and different types of diurnal rainfall variation in the North China Plain. The results of this study can provide valuable information for further mechanism studies, and the proposed approach can serve as a useful tool for studies on diurnal rainfall variation in other regions.

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