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Research Article

Characteristics of Summer Precipitation in Chongqing Based on Hourly Rain Gauges Data

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Based on the hourly precipitation data of 34 meteorological stations in Chongqing in the summers (June to August) from 1996 to 2015, the spatial distribution and daily variation of precipitation amount (PA), precipitation intensity (PI), precipitation frequency (PF), and precipitation extremes in Chongqing are analyzed. The results show that, from the perspective of spatial distribution, the precipitation amount (PA) in Chongqing presents a distribution pattern of more around and less in the middle; the area with high precipitation intensity (PI) is mainly located in the northeast of Chongqing; the large value centers of precipitation frequency (PF) are located in the south and west of Chongqing and near Chengkou. On the spatial distribution of hourly precipitation, the precipitation in most areas of Chongqing is mainly concentrated at night [0200–0900 BT (1800–0100 UTC)], and the rain belt spreads from west to east with the passage of time. On the whole, interannual evolution characteristics of summer precipitation amount, precipitation intensity, and precipitation frequency in Chongqing are basically the same, showing a fluctuation characteristic without obvious trend, but there are some peaks and valleys. From the perspective of diurnal cycle, a larger peak of PA in Chongqing appears near 0300 BT (1900 UTC), another lower peak around 1200 BT (0400 UTC), a larger peak of PI around 0300 BT (1900 UTC), another smaller peak around 1500 BT (0700 UTC), and only one peak of PF around 0700 BT (2300 UTC). The extreme precipitation of different duration in summer in Chongqing is closely related to the topographic characteristics and weather system, the extreme centers of each diachronic precipitation are mainly located near Shapingba, Kaizhou, Youyang, and Shizhu, and the time evolution characteristics of the extreme precipitation are not obvious, but the trend of the extreme precipitation accumulated in 1 h, 3 h, 6 h, or 12 h is basically the same.

1. Introduction

Between 1880 and 2012, the global average surface temperature increased by 0.85°C [1]. In the case of global warming, the temporal and spatial distribution of precipitation has also changed [1]. Many related studies use hourly precipitation data to describe these climate-related changes. The temporal and spatial characteristics of diurnal variation of precipitation are of great significance for revealing the changes of soil moisture, sensible heat, and latent heat in the surface and atmosphere.

The study on the diurnal variation characteristics of precipitation can help us to understand the physical mechanism of precipitation and improve the precipitation parameterization scheme in the numerical model; short-term heavy precipitation is one of the severe convective weather conditions, because it occurs suddenly and because of its short duration, high intensity, and other characteristics, and it is very easy to induce secondary disasters such as mountain torrents, debris flows, and urban waterlogging, which pose a serious threat to people's lives. Therefore, many scholars have analyzed the diurnal variation of precipitation and the climatic characteristics of short-duration heavy precipitation around the world [2, 3]; they have studied the characteristics and diurnal variation of precipitation in Britain and India, respectively. A number of scholars [4–9] analyzed the diurnal variation characteristics of precipitation in China and different regions. Yu et al. [4] found that the diurnal variation of summer precipitation in adjacent areas of China is large, with obvious regional characteristics. Chen et al. [5] found that the daily variability of spring precipitation in Southeast China is weak; the early peak precipitation in the Western Pacific is mainly caused by the increase of rainfall frequency and daily variation of heavy rainfall rate; the peak rainfall in the afternoon has become a significant feature of southern China. Tang et al. [6] found that the maximum frequency of hourly precipitation in various seasons in Southwest China is relatively scattered, but night rain is frequent in some areas of Sichuan, Chongqing, and Guizhou, while the precipitation in Yunnan is mainly daytime precipitation. Bao et al. [7] found that there are strong diurnal variations in summer precipitation in strategic areas in the eastern Tibetan Plateau, and the diurnal cycles are very different among regions and during the early, middle, and late Meiyu periods. Wu and Zhan [9] found that most of the precipitation in Poyang Lake basin occurred from March to June; spatially, the precipitation hours and frequency of precipitation events at most stations in the north of Poyang Lake basin increased significantly, and the heavy precipitation at some stations in the central region increased significantly. Weixin et al. [8] found that the average duration of precipitation events in central and eastern China is "short, long and short" from south to north. There are likewise some studies on the diurnal variation characteristics of precipitation in various provinces of China [10–19]. For example, Li et al. [10] found that the rainfall and rainfall frequency in Beijing have larger values from late afternoon to early morning and reach the lowest values around noon. Mu et al. [12] believe that the daily precipitation frequency in flood season in Shanghai shows obvious bimodal characteristics. Sun et al. [13] found that the hourly heavy precipitation in Guangdong mostly occurs in three rainy areas; the daily variation of hourly heavy precipitation in August is a bimodal structure; the concentration period of hourly heavy precipitation is from [1300–1900 BT (0500–1100 UTC)] every day; the hourly heavy precipitation is basically consistent with the trend of mountains. Wu et al. [15] found that the annual frequency of extreme precipitation events in Xiamen shows a decreasing trend. Su et al. [18] found that the annual precipitation in Yunnan increases from northwest to south, and the rainfall intensity increases from north to south. Miao et al. [19] found that the spatial distribution of extreme precipitation in Shanxi is characterized by greater mountains than basins and is greater in the south than in the north; the strong precipitation of different durations mainly occurs from July to August every year. Xie et al. [20] found that the spatial distribution patterns of the maximum 1, 3, 6, and 12 hours' accumulated precipitation in Anhui Province are basically the same, and the local characteristics of extreme heavy precipitation are obvious, which mainly occurs in the Meiyu period, as well as the heavy precipitation caused by typhoon. Some scholars [21–24] have made some studies on the diurnal variation of precipitation and short-duration precipitation in Sichuan-Chongqing region. Li et al. [21] found that the intellectual and diurnal variations of heavy precipitation in Sichuan Basin are consistent; the intensity, frequency, and precipitation of heavy precipitation events at different starting times have consistent diurnal variation characteristics, and the characteristics of heavy precipitation events at night are obvious. Fang et al. [22] used CMORPH data to find that the precipitation in Chongqing is mainly concentrated from May to September, and the precipitation amount, precipitation intensity, and hourly heavy precipitation frequency all show a single peak distribution. There are obvious characteristics of diurnal variation, and the precipitation is dominated by night rain. Yang et al. [23] found that the spatial distribution of precipitation ratio, proportion of heavy precipitation, frequency of heavy precipitation, heavy precipitation events, extreme precipitation, and extreme precipitation threshold in Chongqing are consistent. In terms of the persistence of heavy precipitation events, the spatial distribution of the duration and the time from the beginning of precipitation to the strongest precipitation are the same. Wang et al. [24] found that the optimal linetypes of different diachronic extreme precipitation in Chongqing are slightly different, the proportion of generalized extreme value distribution is the largest, the three-parameter Weibull distribution is the second, the three-parameter lognormal distribution is the third, the Pearson II distribution is similar to the Gumbel distribution, and the exponential distribution is the worst. In recent years, there have been many studies on extreme precipitation. For example, Zhao et al. [25] studied the diurnal variation of summer precipitation in the Yellow River Basin by using the hourly precipitation data of 481 stations in the Yellow River Basin from 1981 to 2013. It is found that the double peaks of daily precipitation appear in the early morning and evening in the lower reaches of the Yangtze River Estuary. Zheng et al. [26] studied the spatial distribution and temporal changes of hourly extreme precipitation and its local environmental influence factors using the hourly precipitation data in Beijing from 1980 to 2020. The study found that both the summer precipitation and frequency of HEP were affected by terrain, and the values were higher in the windward slope area. Wu et al. [27] used hourly precipitation data of 61 rain gauges from 1971 to 2016 to investigate the variation of extreme hourly precipitation (EXHP) in the Pearl River Delta (PRD) region of South China. Sen Roy and Rouault [28] analyzed hourly precipitation data at 102 stations in South Africa from 1998 to 2007 to understand trends in extreme hourly precipitation events.

Chongqing is the youngest municipality directly under the central government and the National Central City, and it is also at the intersection of "Belt and Road" and the Yangtze River Economic Belt. Seasonal intense rainfall is a common meteorological disaster in Chongqing, which often leads to secondary disasters such as landslide, urban waterlogging, and farmland waterlogging. For example, on July 17, 2017, the central urban area of Chongqing and its surrounding areas suffered a once-in-a-century torrential rain, causing serious floods and property damage [5, 29–33]. Therefore, it is of great significance to analyze the characteristics of

Chongqing's short-term heavy precipitation, especially the temporal and spatial evolution characteristics of summer hourly precipitation. This paper attempts to reveal the temporal and spatial characteristics of Chongqing's total precipitation, frequency, intensity, and extreme value through statistics and analysis of the daily variation of Chongqing's summer hourly precipitation in 20 years and short-term heavy precipitation in different duration. The conclusions of this study can provide some references for the prevention of disasters caused by short-term heavy precipitation in Chongqing.

2. Overview of the Study Area

Figure 1 shows the relative position of Chongqing in China and the distribution map of 34 national basic weather stations, which is located in the transitional zone of China's primary and secondary topography, that is, the eastern part of the Sichuan basin (28 N~32.5 N, 105 E~110.5 E, as shown in Figure 1(a)). In the west there is the basin topography. In the south there are the Wuling Mountains trending southwest to northeast, and the north is close to the Qinling-Daba Mountains, and the Yangtze River flows from southwest to northeast. It is the transitional zone [7] between the Tibetan plateau and the plain of the middle and lower reaches of the Yangtze River. Its unique topography is undoubtedly one of the areas with the richest temporal and spatial distribution characteristics of precipitation and the most significant regional characteristics, belonging to the humid monsoon climate in the middle subtropics. The average annual precipitation is about 1200 mm, and the precipitation concentration period is mainly from night to early morning, which spreads from west to east, and the precipitation is of high frequency and intensity during the warm season [6, 18, 21]; secondary disasters induced by heavy precipitation (such as mountain torrents, landslides, and debris flows) have a serious impact on Chongqing's economic and social development and the safety of people's lives and property [5, 29–33]. Considering the differences in topography and climate characteristics, Chongqing is divided into six regions: the west, the southwest, the central urban area, the central, the southeastern, and the northeastern areas (Figure 1(b)). The central urban area represents the city and population gathering area, the west represents the Chengdu-Chongqing Shuangcheng Economic Circle, dominated by plains and hills, and the southwest represents the mountainous area south by west. Mainly affected by the weather system in the north of Guizhou, the central part represents the transitional zone between the basin and the mountain, while the northeast and southeast represent the mountain region, respectively. This zoning standard has been applied in the daily weather operation of Chongqing. In this study, according to the topographic characteristics of each region, the precipitation characteristics and regional differences of each region are discussed.

The rest of this article is organized as follows: The third section introduces the data and methods, and the fourth section is the main result, which introduces the spatial distribution characteristics of summer hourly precipitation in Chongqing, the annual variation of summer regional average PA, PI, and PF, and the summer regional average and the diurnal variation of PA, PI, and PF in different regions and analyzes the spatial distribution characteristics of hourly precipitation in Chongqing; Finally, the spatial distribution and temporal evolution of different diachronic precipitation extremes are analyzed. The fifth section is summary and discussion.

3. Materials and Methods

3.1. Materials. The data used in this study come from the hourly self-recording precipitation dataset of 34 national surface meteorological stations in Chongqing provided by Chongqing Meteorological Information and Technical guarantee Center (Figure 1). The data period is the summers (June–August) of 1996–2015. The observation instruments are siphon or double bucket rainfall sensors. The agreed hourly precipitation refers to the accumulated precipitation one hour before that time; for example, 08 : 00 (Beijing time) hourly precipitation refers to the one-hour precipitation from 07 : 00 to 08 : 00. The extreme precipitation data of different durations (1 h, 3 h, 6 h, and 12 h) are taken from the monthly report of original meteorological records and its information products filed in the reference room of Chongqing Meteorological Bureau. The data were tested by extreme value test and comprehensive quality control such as time consistency, internal consistency, and spatial consistency [11]. The basic information of each station is shown in Table 1.

3.2. Methods. In this study, Chongqing is selected as the research area, and it is classified according to the topography and administrative territorial entity, including the basin area in the west of Chongqing, the mountain area in the northeast, and southeast of Chongqing. Referring to the practice of [12, 16], the hourly precipitation greater than or equal to 0.1 mm is taken as the basis for precipitation; that is, when the hourly precipitation is greater than 0.1 mm, it is recorded as a precipitation event. The precipitation amount, precipitation frequency, and precipitation intensity are introduced to analyze the precipitation characteristics of Chongqing from 1996 to 2015. In particular, the temporal and spatial characteristics of hourly precipitation and extreme precipitation in different duration are analyzed. The specific definitions are as follows: (1) precipitation amount (PA) is defined as the cumulative hourly precipitation in summer (1996–2015) divided by 92 days (total precipitation divided by total hours), which is used to describe the precipitation per unit time. (2) Precipitation intensity (PI) is defined as the climate average value of JJA cumulative hourly precipitation divided by the number of measurable precipitation days during JJA (total precipitation divided by total precipitation hours); that is, precipitation intensity = precipitation/precipitation frequency, which is used to describe the average intensity of precipitation when there is actual precipitation. (3) Precipitation frequency (PF) refers to the time of precipitation * 100/total time (total

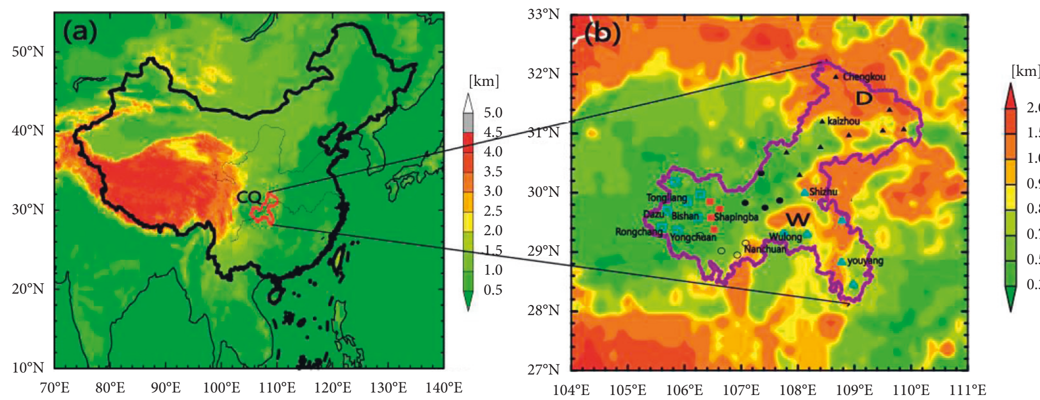

Figure 1: (a) The location of Chongqing, where the thick red lines represent Chongqing; the thin solid lines within China represent the Yangtze River and the Yellow River. (b) The topography of Chongqing (color-shaded area; unit: km) and 6 climate operation divisions, in which the red solid box represents the central urban area, the blue hollow box represents the western region, the black hollow circle represents the southwest, the black solid circle represents the central region, the black solid triangle represents the northeast, the blue solid triangle represents the southeast, and D and W represent the Daba Mountain and Wuling Mountain.

Table 1: Basic situation of 34 stations in Chongqing.

Station name	Station number	Longitude (E)	Latitude (N)	Altitude (m)
Chengkou	57333	108° 40′	31° 57′	800.0
Kaizhou	57338	108° 26′	31° 12′	166.4
Yunyang	57339	108° 54′	30° 58′	206.5
Wuxi	57345	109° 37′	31° 24′	339.8
Fengjie	57348	109° 30′	31° 03′	608.3
Wushan	57349	109° 52′	31° 04′	270.8
Tongnan	57409	105° 50′	30° 11′	248.1
Dianjiang	57425	107° 21′	30° 20′	418.2
Liangping	57426	107° 48′	30° 41′	459.4
Wanzhou	57432	108° 24′	30° 46′	188.8
Zhongxian	57437	108° 02′	30° 18′	232.2
Shizhu	57438	108° 07′	30° 00′	569.5
Dazu	57502	105° 42′	29° 42′	393.6
Rongchang	57505	105° 36′	29° 25′	330.0
Yongchuan	57506	105° 53′	29° 22′	319.6
Wansheng	57509	106° 56′	28° 57′	325.7
Tongliang	57510	106° 03′	29° 51′	282.1
Beibei	57511	106° 27′	29° 51′	242.9
Hechuan	57512	106° 17′	29° 58′	231.1
Yubei	57513	106° 38′	29° 43′	438.0
Bishan	57514	106° 14′	29° 35′	289.2
Chongqing	57516	106° 28′	29° 35′	260.4
Jiangjing	57517	106° 17′	29° 17′	209.0
Banan	57518	106° 31′	29° 23′	205.1
Nanchuan	57519	107° 05′	29° 09′	559.5
Changshou	57520	107° 04′	29° 50′	379.0
Fuling	57522	107° 25′	29° 45′	274.1
Fengdu	57523	107° 41′	29° 52′	214.8
Wulong	57525	107° 45′	29° 19′	406.4
Qianjiang	57536	108° 47′	29° 32′	608.8
Pengshui	57537	108° 10′	29° 18′	321.5
Qijiang	57612	106° 39′	29° 01′	252.7
Youyang	57633	108° 46′	28° 50′	665.8
Xiushan	57635	108° 59′	28° 27′	363.5

precipitation hours divided by total hours) in the statistical period. This quantity refers to the frequency of precipitation events. The formulas of PA, PI, and PF are as follows:

$$PA = \frac{\sum_{t=1}^{n} P_t}{n}, \quad (1)$$

$$PI = \frac{\sum_{t=1}^{n} P_t}{\sum_{t=1}^{n} i}, \quad (2)$$

$$PF = \frac{\sum_{t=1}^{n} i}{n}, \quad (3)$$

and when $P_t \geq 0.1mm$, $i = 1$; otherwise, $i = 0$ (2), and when $P_t \geq 0.1mm$, $i = 1$; otherwise, $i = 0$ (3).

The data of annual maximum precipitation from 1991 to 2015 are read directly from the audited annual report of surface meteorological records. The maximum precipitation data sets of 4 different durations (1, 3, 6, and 12 hours) from 1991 to 2015 were collated and formed.

4. Results

4.1. Spatial Distribution Characteristics of Summer Hourly Precipitation in Chongqing. Summer is the primary precipitation season in the whole year. As can be seen from the spatial distribution map of precipitation (PA) (Figure 2(a)), it generally presents a distribution pattern of more around and less in the middle, roughly located in Kaizhou, Youyang, Nanchuan, Rongchang, Bishan. and Shapingba. The spatial distribution map of precipitation intensity (PI) (Figure 2(b)) is about different from the distribution of precipitation (PA); that is, the high value area of precipitation intensity is mainly located in the northeast of Chongqing, and there are also high value centers near Youyang, Shapingba, and Tongliang; From the spatial distribution map of precipitation frequency (Figure 2(c)), it can be seen that there are large value centers in the south and west of Chongqing and near Chengkou.

As can be seen from Figure 2(a), the precipitation is high in the periphery and low in the middle, and the strongest center is located at the junction of Wuxi, Yunyang, and Fengjie in the northeast (0.31 mm/h), which is related to the frequent activity of the southwest vortex in summer and the westward extension and northward uplift of the western Pacific subtropical high [34–36].

Through analysis, it can be found that the summer hourly precipitation in Chongqing has different characteristics compared with Shandong, Shanghai, Beijing, Tianjin, and other regions [12, 16, 29].

4.2. Extreme Precipitation. We use the hourly peak PA/PF/PI (hereinafter referred to as PPA/PPI/PPF) in one day (24 hours) to reveal the spatial and daily variation characteristics of PA/PI/PF. Figure 3(a) shows the horizontal distribution of PPA. Generally speaking, large PPA values are displayed in the west, the west by northeast, and the southeast of Chongqing. At the same time, from the southwest of Chongqing through the middle to the east by northeast is the low value area of PPA. That is, PPA is higher in the northwest and the southeast and lower in the middle. The high value area of PPA (greater than or equal to $0.38\,\mathrm{mm{\cdot}h^{-1}}$) occurs on the south slope of Daba Mountain (represented by A), the east side of Wuling Mountain (represented by B), and the parallel ridge valley area in the west of Chongqing (represented by C) (Figure 3(a)). The PPA area below $0.3\,\mathrm{mm{\cdot}h^{-1}}$ is fairly consistent with the trend of the Yangtze River, mainly in the southwest of Chongqing and the east of the northeast, with a southwest-northeast trend. Similar to the distribution of PPA, large PPI greater than $2.8\,\mathrm{mm{\cdot}h^{-1}}$ mainly occurs on the windward side of Daba Mountain and in the northwest and southwest of Chongqing (Figure 3(b)). In addition, high value PPI also appears in the southeast side of Wuling Mountain, and its center is located near Youyang. Areas with PPI lower than $2.3\,\mathrm{mm{\cdot}h^{-1}}$ appear in the main urban area of Chongqing and near Wulong. Different from PPA, the area with high PPF value is placed in the central and western parts of Chongqing, which generally decreases from the western part of Chongqing to the eastern part of Chongqing. The low PPF value appears in the eastern part of Chongqing and gradually decreases in the southwest northeast direction (Figure 3(c)).

4.3. Interannual Variability of Precipitation. Figure 4 shows the interannual variation time series of precipitation amount (PA), precipitation intensity (PI), and precipitation frequency (PF) in Chongqing from 1996 to 2015. It can be seen that the overall trend of annual precipitation amount, precipitation intensity, and precipitation frequency in recent years is basically the same, showing a fluctuation characteristic without obvious trend, but there are several peaks and valleys, the peaks are in 1996, 1998, 2007, and 2009 respectively, and the valleys are in 2001 and 2006, respectively. However, in 2011, 2012, and 2013, PI and PF showed an inverse phase; that is, the rainfall in recent years was strong, but the precipitation frequency was low, so the total precipitation amount (PA) was relatively low. This result further supports the finding of Zhou et al. [33]. Their research demonstrates that the diurnal variation of PA in most parts of eastern China can be attributed to PI and PF. It shows that although the precipitation frequency in Chongqing has decreased in recent years, the intensity of precipitation has increased obviously.

4.4. Diurnal Cycle of the Precipitation in Chongqing and Subregions. Figure 5 shows the diurnal variation evolution of regional average PA, PI, and PF in Chongqing. It can be seen from the figure that PA and PI have two peaks. For PA, a larger peak appears near 0300 BT (1900 UTC) and another lower peak appears near 1200 BT (0400 UTC). For PI, a larger peak appears near 0300 BT (1900 UTC) and another smaller peak appears near 1500 BT (0700 UTC). PF has only one peak, which occurs around 0700 BT (2300 UTC). According to the definition in Section 2, PA can be determined jointly by PF and PI. When precipitation is frequent (such as monsoon precipitation) or in short duration but with high intensity (such as convective precipitation), PA is

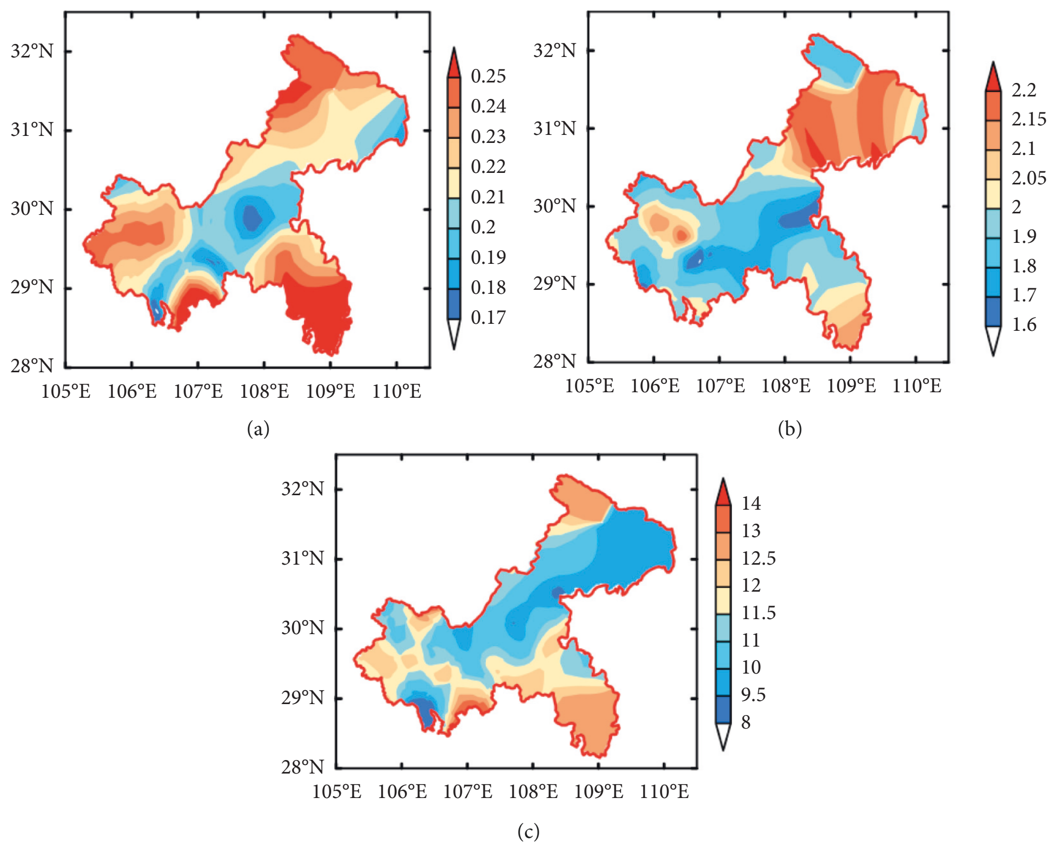

Figure 2: (a) Summer precipitation amount spatial distribution map (unit: mm·h^{-1}); (b) summer precipitation intensity PI spatial distribution map (unit: mm·h^{-1}); (c) summer precipitation frequency spatial distribution map (unit: %).

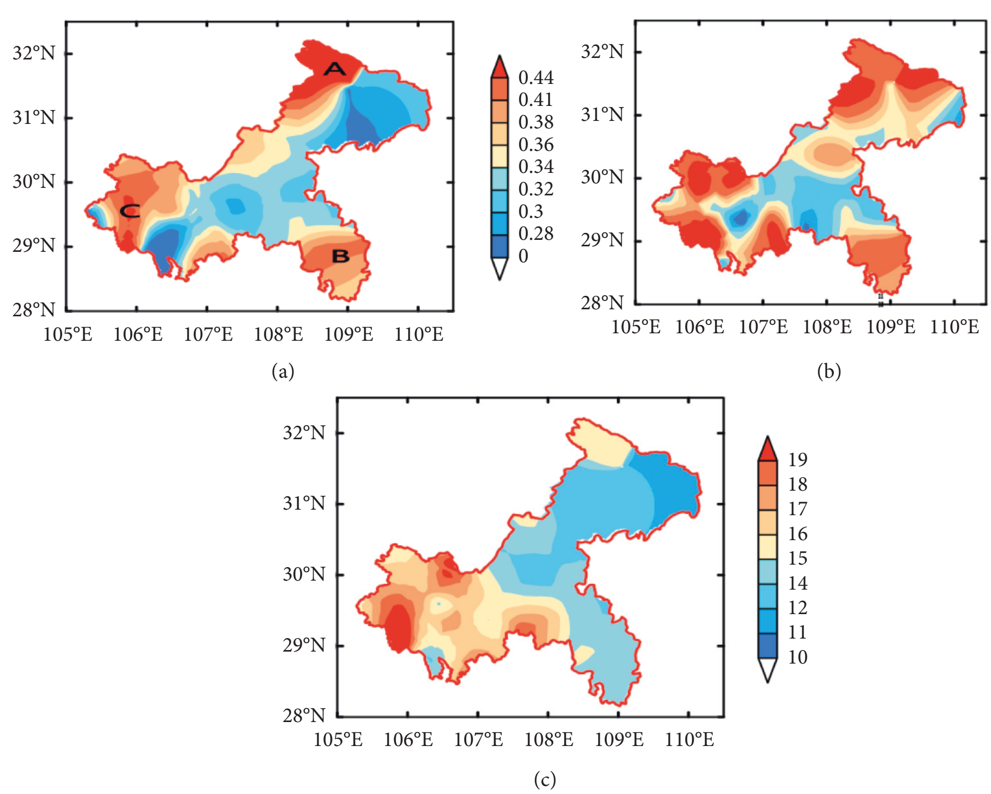

Figure 3: (a) Spatial distribution map of summer extreme precipitation amount (unit: mm·h^{-1}); (b) spatial distribution map of summer extreme precipitation intensity (unit: mm·h^{-1}); (c) spatial distribution map of summer extreme precipitation frequency (unit: %).

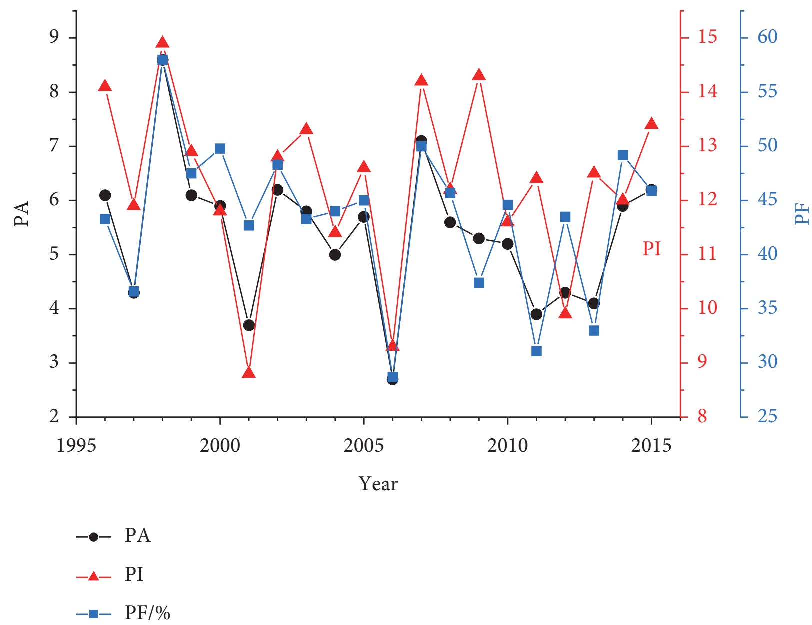

Figure 4: Annual changes of summer average PA (mm·h^{-1}, black solid circle), PI (mm·h^{-1}, red solid triangle), and PF (%, blue solid square) in Chongqing. The x-axis is the year.

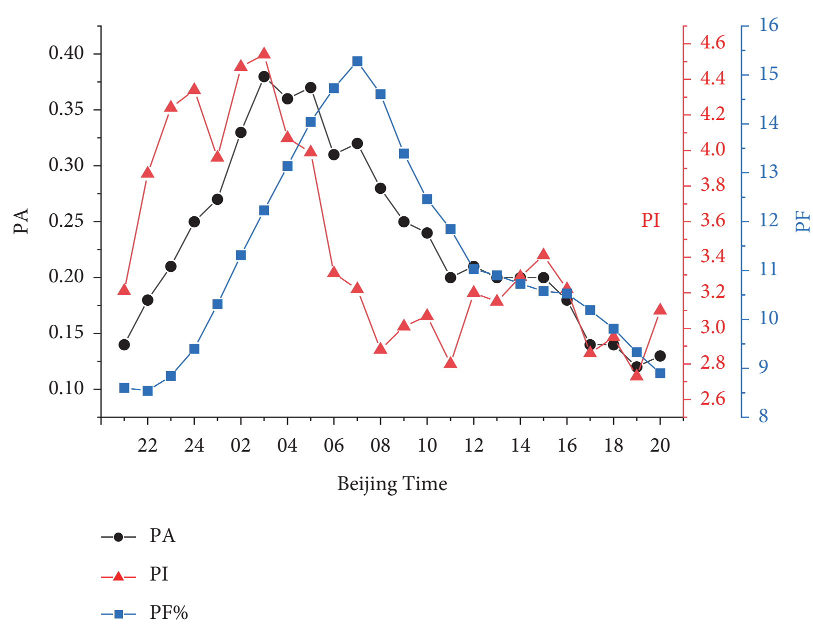

Figure 5: Daily variation of average PA (mm·h^{-1}, black solid circle), PI (mm·h^{-1}, red solid triangle), and PF (%, blue solid square) in Chongqing in summer. The x-axis is Beijing time (unit: h).

larger. Therefore, the larger peak of PA near 0300 BT (1900 UTC) may be determined by PF, while the smaller peak of PA near 1200 BT (0400 UTC) may be determined by PI. This result further supports the conclusion of Zhou et al. [33]. Their study shows that the daily variation of PA in most parts of eastern China can be attributed to PI and PF.

Depending upon the research of Yu et al. [4], according to objective zoning (Figure 1(b)), Chongqing is further divided into 6 regions (as shown in Figure 1(b)). Figure 6 shows the daily changes of multiyear average PA, PI, and PF in six regions of Chongqing from 1996 to 2015. As can be seen from the Figure, PA has a single peak in three of the six regions (i.e., the western, the middle, and the central urban area), with the peak in the early morning (03 : 00, 08 : 00, and 07 : 00, respectively), and the other three regions (i.e., the southwest, southeast, and northeast) have a double peak, with the larger peak at 04 : 00, 06 : 00, and 08 : 00, respectively, and the secondary peak around the evening, that is, 18 : 00, 16 : 00, and 17 : 00 (Figure 6(a)). This is similar to the results of Yang et al. [19, 25, 37]. Their research shows that,

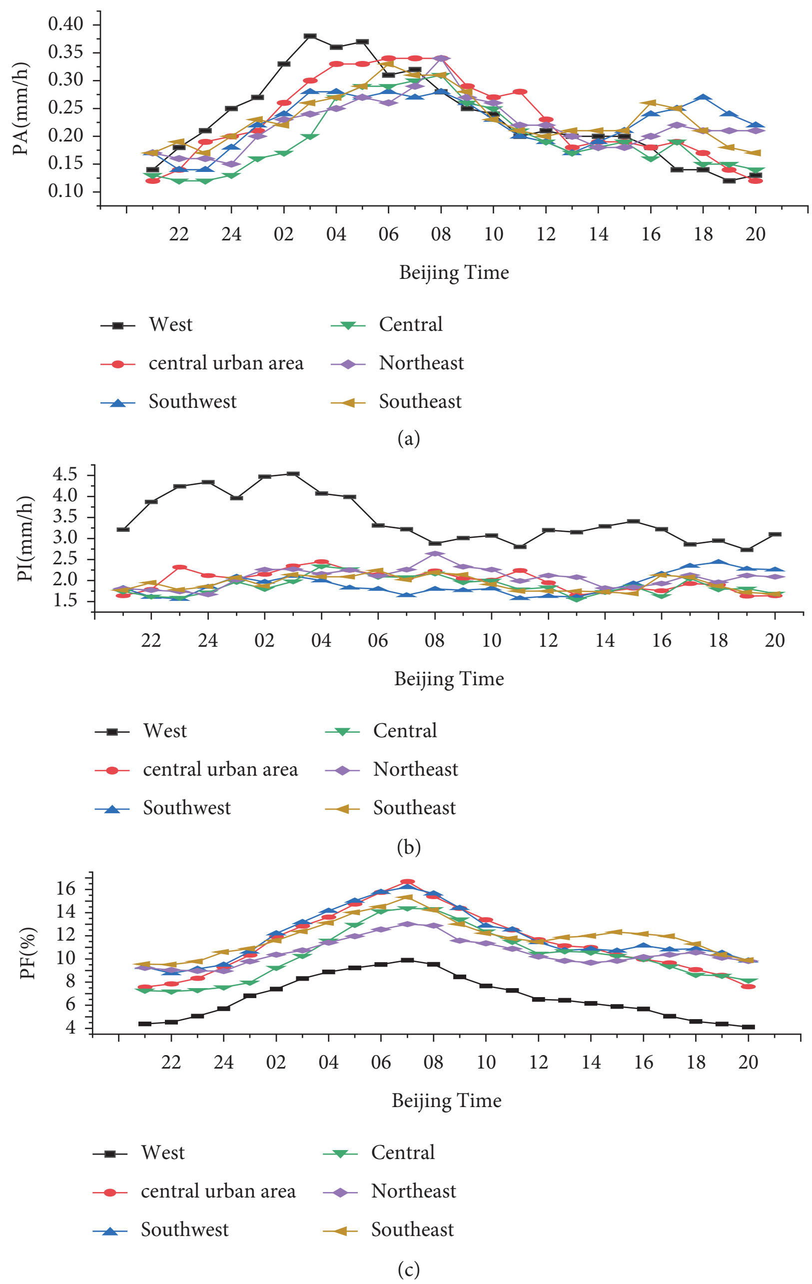

FIGURE 6: The diurnal variation of summer average PA (unit: mm·h^{-1}), PI (unit: mm·h^{-1}) and PF (unit: %) in 6 regions of Chongqing. The *x*-axis is Beijing time (unit: h). West (black solid square), downtown (red solid circle), southwest (blue solid triangle), central (green solid inverted triangle), northwest (purple solid diamond), and southwest (brown solid left triangle).

in the Yellow River and adjacent waters, the peak of PA often occurs in the early morning rather than in the afternoon.

For PI (Figure 6(b)), the west, northeast, and southwest are bimodal. The larger value areas are at 03, 08, and 18 hours, respectively, and the secondary peak areas are at 15, 17, and 03 hours, respectively. This may indicate that there is a peak of 4.0–4.5 mm·h^{-1} in the late night (between midnight and 0800 BT). In addition, local convective activity due to geothermal fluxes caused by solar radiation was at another peak in the late afternoon.

The PF peak in 6 regions (Figure 6(c)) occurs in the early morning mainly (0700 BT). Generally speaking, occurrence time of PF peak in different regions is basically the same, which may reflect the influence of large-scale weather system. Another weak peak appears around the evening in the southwest, southeast, and northeast (1600, 1500, and 1800 BT, respectively), which may indicate the influence of local thermal convection in the afternoon.

4.5. Spatial Distribution of Hourly Precipitation. From the spatial distribution of precipitation at different time (Figure 7), most of the precipitation in Chongqing is mainly concentrated at night (02 : 00–09 : 00), and the rain belt

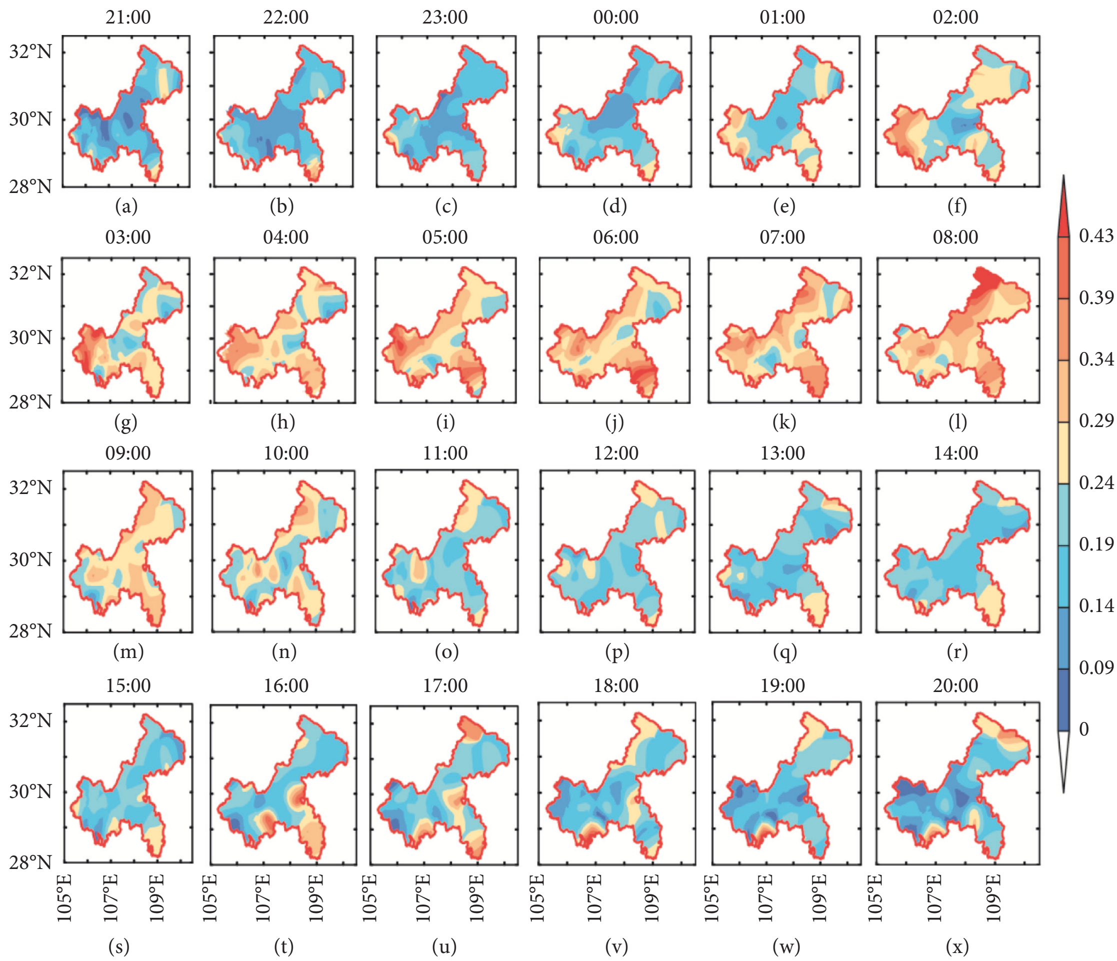

Figure 7: Spatial distribution of hourly average precipitation in summer from 1996 to 2015 in Chongqing (unit: mm·H^{-1}): (a-x) 21 : 00 to 20 : 00 the next day (Beijing time, the same below).

spreads from west to east with the passage of time. In the western basin, it reached its peak at 02, and the lowest was at 18 : 00; the western basin peaked at 02 : 00–05 : 00 and reached its lowest level at 18 : 00. The central and southeastern mountains peak around 06 : 00, and 21 : 00 was the lowest throughout the day. The northeast mountain area reaches its peak around 08 : 00 and the lowest around 22 : 00. This is basically consistent with the conclusion that the precipitation in southwest China is dominated by night rain, and the occurrence time of the peak precipitation is delayed from west to east, which is pointed out in the previous study [4, 7]. The difference is that the occurrence time of the peak precipitation in Chongqing is not completely from west to east, but from southwest to northeast, which is basically the same as that of the mountains in Chongqing. From the spatial distribution of precipitation at different times, at 18 : 00 (Figure 7(v)), the precipitation is less in Dazu, Rongchang, and Yongchuan in the west (the least in the whole day), followed by the middle and southeast, and stronger in the northeast. The precipitation in the west began to strengthen at 21 : 00 (Figure 7(a)), and the precipitation in the central and northeast regions further weakened, and the areas with less precipitation increased and moved eastward. It can be seen from Figure 7(g) (03 : 00) that the total precipitation is high in the south and low in the north; the precipitation reaches the peak in the west and continues to strengthen in the middle, southeast, and northeast. At 06 : 00 : 00 (Figure 7(j)), the total precipitation was the strongest in the central and southeast, reaching the peak, the precipitation began to weaken in the west and continued to strengthen in the northeast, and at 09 : 00 : 00 (Figure 7(m)) the total precipitation was high in the east and low in the west. After reaching the peak, the northeast began to weaken, while the precipitation in the west, center, and southeast continued to weaken. By 12 : 00 : 00 (Figure 7(p)), the total precipitation of each region further decreased, the maximum area was in the northeast, followed by the southeast, and the precipitation in the west and middle was lower; from Figure 7(s) (15 : 00), it can be seen that there is more precipitation in the mountainous areas on both sides of the Yangtze River in the northeast. The precipitation in the valley is less, and the precipitation continues to decrease in the west and southeast.

According to the spatial distribution of precipitation frequency in different times (picture omission), the areas with higher precipitation frequency mainly appear in the mountains of Daba Mountain, Wushan Mountain, and

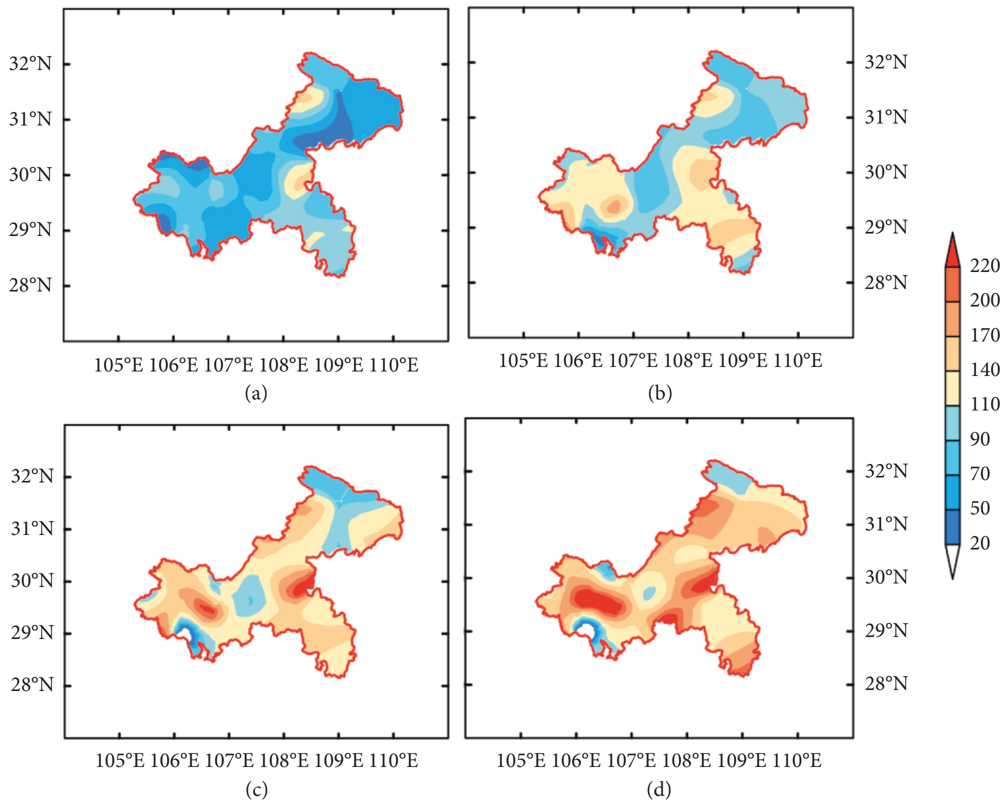

Figure 8: Distribution of extreme precipitation in different durations in Chongqing: (a) 1 hour, (b) 3 hours, (c) 6 hours, and (d) 12 hours.

Table 2: Statistical characteristics of extreme precipitation of different duration in Chongqing.

Different duration (h)	Max (mm)	Min (mm)	Amplitude (times)	Number of sites			
				≥80 mm	≥120 mm	≥150 mm	≥180 mm
1	115.9	50.8	2.3	13			
3	167.8	75.7	2.2		11		
6	218.7	89.4	2.4			11	
12	253.3	107.6	2.4				9

Wuling Mountain: from 20 : 00 to 09 : 00, the regions with high precipitation frequency mainly appear in the west, middle, and southeast, and, with the passage of time, and, from 00 : 00, the precipitation frequency in the west gradually increases, which is consistent with the change of precipitation. Judging from the spatial distribution of precipitation intensity at different times (picture omission), the precipitation intensity increases gradually from 19 : 00 in the west to a peak at 03 : 00 the next day and then weakens; it strengthens at 22 : 00 in the middle, reaches a peak at 05 : 00 the next day, increases in the southeast, reaches a peak at 06 : 00 the next day, increases in the northeast at 16 : 00, and reaches a peak at 08 : 00 on the next day.

4.6. Extremes of Precipitation in Different Duration. Based on the hourly precipitation data of 34 national stations in Chongqing in the recent 25 years, the maximum precipitation of 1 h, 3 h, 6 h, and 12 h in each station is extracted. The results show that the maximum precipitation in one hour appears in all 34 meteorological stations in Chongqing. The historical maximum hourly rainfall intensity varies from 50.8 mm (Yunyang) to 115.9 mm (Shizhu) (Figure 8(a), Table 2). The maximum precipitation ≥80 mm in one hour mainly occurs in Wuling Mountain and Daba Mountain. It mainly includes Kaizhou, Liangping, Zhongxian, Shizhu, Dazu, Tongliang, Yubei, Bishan, Jiangjin, Wulong, Pengshui, Youyang, Xiushan, and other places [Figure 1(b)].

The historical maximum 3 h rainfall intensity at each station is 75.7 mm (Fuling) to 167.8 mm (Banan) [Figure 8(b) Table 2]. The maximum rainfall intensity ≥120 mm occurs in Rongchang, Yongchuandslft, Tongliang, Beibei, Yubei, Shapingba, and Banan in the west of Chongqing, Shizhu, and Youyang in the southeast, Kaizhou and Zhongxian in the northeast, and Fuling in the middle of Chongqing [Figure 1(b)].

The largest 6 h rainfall intensity in history is 89.4 mm (Chengkou) to 218.7 mm (Shapingba) [Figure 8(c) Table 2]. The maximum rainfall intensity ≥150 mm occurs in Rongchang, Yongchuan, Tongliang, Beibei, Hechuan, Bishan,

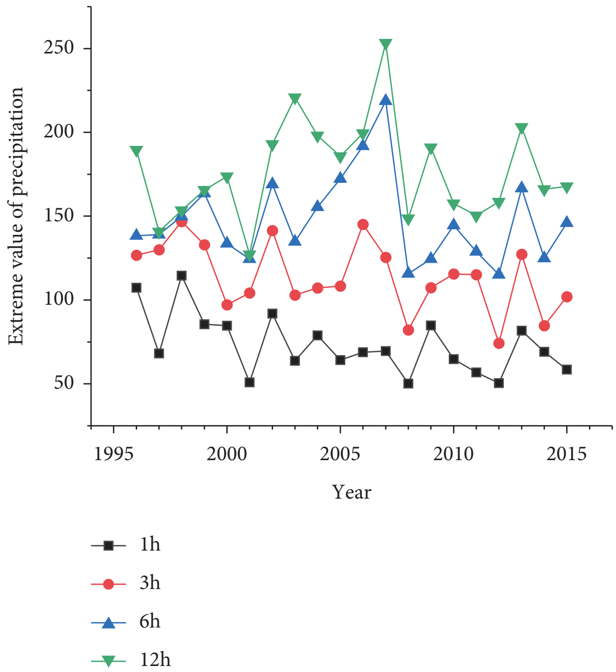

Figure 9: Interannual variation of extreme precipitation in different durations in Chongqing.

Shapingba, and Banan in the west of Chongqing, Kaizhou, and Liangping in the northeast and Shizhu in the southeast (Figure 1(b)).

The maximum rainfall intensity of 12 h ranges from 107.6 mm (Chengkou) to 253.3 mm (Bishan) [Figure 8(d), Table 2]. The maximum rainfall intensity of 12 h precipitation ≥180 mm mainly occurs in Tongliang, Yubei, Bishan, Shapingba, and Banan in the west of Chongqing, Wulong, and Xiushan in the southeast, Shizhu in the southeast and Kaizhou in the northeast [Figure 1(b)].

From the distribution map of the maximum precipitation of 1 h, 3 h, 6 h, and 12 h at each station (Figure 8), it can be seen that the difference between the maximum precipitation and the minimum precipitation is 2.2–2.4 times (Table 2). The distribution pattern of maximum precipitation in each period is basically the same; there are no obvious meridional or zonal spatial distribution characteristics, but there are several large value centers, that is, Shapingba, which is located in the central city of Chongqing. The second is near Kaizhou in the northeast of Chongqing, the third is located in Youyang in the southeast of Chongqing, and the last one is located near Shizhu in the southeast of Chongqing. The above analysis shows that the extreme value of summer precipitation in Chongqing in recent 25 years is closely related to topographic characteristics and weather system. This is due to the fact that the heavy precipitation in most areas of Chongqing is greatly affected by the advance and retreat of the summer monsoon and the western Pacific subtropical high, and the prevailing southwest wind or southerly wind in summer, coupled with the special topographic influence, leads to a large extreme value of short-duration heavy precipitation.

Figure 9 shows the annual evolution sequence of precipitation extremes in different duration. Generally speaking, there are a peak (2007, 12 h precipitation extreme value is 253.3 mm) and a valley value (12 h precipitation extreme value is 127.2 mm in 2001). The amplitude of other periods is not large, but the variation trend of precipitation extreme value is basically the same whether 1 h, 3 h, 6 h, or 12 h. From the evolution of precipitation extreme value of different duration, the extreme value of 1 h precipitation is 114.6 mm and 107.4 mm in 1998 and 1996, respectively, the extreme value of 3 h precipitation appears in 1998 and 2006, the peak is 146.8 mm, 145.1, mm and 146.8 mm, the peak value of 6 h precipitation is 218.7 mm in 2007, and the extreme value of 12 h precipitation also appears in 2007, where the peak value is 253.3 mm.

5. Summary and Discussion

Through the analysis of the hourly precipitation data of Chongqing from 1996 to 2015, the understanding of precipitation characteristics in Chongqing is deepened. Focusing on the daily variation of precipitation, the average characteristics, interannual variation, diurnal variation and regional differences of precipitation amount, and precipitation intensity and precipitation frequency are analyzed, and the spatial distribution and temporal evolution of precipitation with different duration are analyzed. The main conclusions are as follows:

First of all, from the perspective of spatial distribution, the precipitation amount (PA) in Chongqing presents a distribution pattern of more around and less in the middle; the area with high precipitation intensity (PI) is mainly located in the northeast of Chongqing; The center of high precipitation frequency (PF) is located in the south and west of Chongqing and near Chengkou. PPA in Chongqing is higher in the northwest and Southeast and lower in the middle; Similar to the distribution of PPA, the PPI greater than 2.8 mm·h^{-1} mainly occurs on the windward side of Daba Mountain, as well as northwest and southwest of Chongqing; the PPF large value area is located in the central and western parts of Chongqing, generally falling from the western part of Chongqing to the eastern part of Chongqing. From the spatial distribution of hourly precipitation, the precipitation in most areas of Chongqing is mainly concentrated at night (02 : 00–09 : 00), and the rain belt is characterized by spreading from west to east with the passage of time.

Secondly, from time evolution characteristics, the interannual evolution characteristics of annual precipitation amount, precipitation intensity, and precipitation frequency in Chongqing are basically the same, showing a fluctuation characteristic, and there are several peaks and valleys. From the daily variation, a larger peak of PA in Chongqing appears near 0300 BT (1900 UTC), and another lower peak appears near 1200 BT (0400 UTC); a larger peak of PI appears near 0300 BT (1900 UTC) and another smaller peak appears near 1500 BT (0700 UTC). PF has only one peak, which occurs around 0700 BT (2300 UTC). From the situation of different regions in Chongqing, the precipitation shows a single peak distribution and has obvious daily variation characteristics. The peak value is reached in the west at 03 : 00 and in the northeast at 08 : 00. The occurrence time of the peak value lags from west to East; the peak time of precipitation frequency in most areas is mainly concentrated at 05 : 00, while in the Northeast it occurs in the afternoon; the regional peaks of precipitation intensity are mainly concentrated in 03 : 00~08 : 00, among which the average precipitation intensity in the northeast and west is strong.

Finally, the extreme value of precipitation in different duration in Chongqing in summer is closely related to topographic characteristics and weather system. The extreme value centers of precipitation in different durations are mainly distributed in four regions, the first is located in Shapingba, the central urban area of Chongqing, the second is located near Kaizhou in the northeast, the third is located in Youyang in the southeast, and the fourth is located near Shizhu in the southeast; The southerly airstream carrying rich water vapor is forced to uplift in the mountain area to produce heavy precipitation. At the same time, evolution characteristics of precipitation extremes in different duration in Chongqing are not obvious, but the variation trend of precipitation extremes in 1 h, 3 h, 6 h, or 12 h is basically the same.

This study is helpful to further understand the diurnal variation characteristics of precipitation in Chongqing and to study the precipitation over complex terrain in southwest China. However, due to the limited data length and the relatively sparse spatial distribution of stations, this study may be further improved in the future work.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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