Regional differences in rainfall frequency and amount over southwestern China

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Hengduan Mountains. The objective of this study is to fully compare the rainfall features over the above three regions, especially information regarding the rainfall frequency. The subdaily rainfall features are also analyzed and then we briefly discuss the possible mechanisms responsible for the different rainfall features. The remainder of the paper is organized as follows. Section 2 briefly describes the datasets and analysis methods employed. In section 3, an analysis of the rainfall features in southwestern China is presented. Finally, a short summary and discussion are given in section 4.

2. Data and methods

Daily records from 1961 to 2013 at 620 stations covering southwestern China are used in this study (Figure 1). The dataset is described in Sun et al. (2015). The data were collected and strictly quality-controlled by the National Meteorological Information Center of the China Meteorological Administration (Ren et al. 2010). The daily rainfall, daily relative humidity, daytime (0800–2000 Beijing Time (BJT)), and nighttime (2000–0800 BJT) rainfall of this dataset are used. A rainy day is defined as a day with ≥0.1 mm of accumulated precipitation, and the mean rainfall frequency is defined as the ratio of rainy days to the number of days with observations. The zonal, meridional, and vertical winds of the Japanese 25-year Reanalysis (JRA-25; Onogi et al. 2007) from March to May of 1979–2013 are used to describe the large-scale circulations. The reanalysis dataset is 1.25° × 1.25° horizontally and contains 23 vertical levels. Previous studies note that JRA-25 is reliable in East Asia (Bosilovich et al. 2008; Zhang and Wang 2008).

3. Results

Figure 2(a) illustrates the annual rainfall amount over southwestern China. Generally, the daily rainfall amount decreases from south to north and from east to west, except for along the western edges of the Hengduan Mountains. Additionally, the rainfall over southwestern China (west of 110°E) also shows distinct regional differences, which present as a western/eastern-flooding-and-center-drought pattern. On the southwestern side of the Hengduan Mountains, there is a belt of large amounts of rainfall. The rainfall amount is low over the mountains. East of the mountains, the rainfall amount reaches a higher level, especially over the lower-topography area (Figure 1). In addition to the rainfall amount, the rainfall frequency can also reflect these characteristics (Figure 2(b)). Similar to the rainfall amount, the rainfall frequency also presents as a western/eastern-flooding-and-center-drought pattern. However, the rainfall frequency (Figure 2(b)) shows a greater contrast than the rainfall amount (Figure 2(a)).

Based on the rainfall frequency spatial distribution, southwestern China is divided into three parts, which are shown in Figure 2. Region (Reg.) 1 (3) represents the region along the western (eastern) edges of the Hengduan Mountains, which have more frequent rainfall, and Reg. 2 encompasses the main body of the mountains where rains occur less frequently. In Regs. 1–3, there are 10, 59, and 99 stations, respectively. The regionally averaged annual rainfall amounts of Regs. 1 and 3 are 3.61 and 3.64 mm d⁻¹, respectively, which are approximately 1.2 times larger than that of Reg. 2 (2.83 mm d⁻¹). For rainfall frequency, the ratio increases.
to 1.4 times. Additionally, in Reg. 3, the spatial distribution of the rainfall amount is nearly the opposite of the rainfall frequency spatial distribution. The rainfall amount is larger over the lower-altitude area, and rain occurs more frequently over the mountain foothills. The spatial correlation between the rainfall amount and frequency over Reg. 3 is approximately \(-0.85\). The spatial correlation shows that the rainfall frequency is also an important factor in studying rainfall characteristics.

Additionally, as illustrated in Figures 1 and 2, the rainfall features are related to the topography. The calculations showed that in Reg. 1, the rainfall amount and frequency are generally positively correlated with terrain height, but these factors are nonsignificant. Because ridges and ravines are found on Reg. 2, the terrain height of the Reg. 2 stations ranges from 800 to 3500 m. However, the dry weather is uniform throughout the entire region. In Reg. 3, the rainfall is significantly negatively correlated with the terrain height, but the correlations between the terrain and rainfall frequency are better than the correlations between the terrain and rainfall amount. As a result, the analyses in the following section are divided into three key regions based on the rainfall features.

To identify the months in which the rainfall contrast is more obvious between Reg. 1/3 and Reg. 2, the deviations between Regs. 1 and 2 during each month, as well as between Regs. 3 and 2, are shown in Figure 3. For the rainfall amount (Figure 3(a)), the regional differences between Regs. 1 and 2 are the most apparent from March to May. On average, the rainfall amount from March to May in Reg. 1 is approximately 2.5 mm d\(^{-1}\) larger than that in Reg. 2. From summer to winter, the rainfall amounts in the two regions are at approximately the same level. The deviation between Regs. 2 and 3 is larger from March to June, and the mean value is approximately 1.9 mm d\(^{-1}\). The deviations among the three regions show similar variations from July to December.

Figure 2. (a) Average annual rainfall amount (units: mm d\(^{-1}\)) and (b) frequency (units: %) during 1961–2013. The black boxes outline the three regions that are the main focus of this study. The white lines represent the Yangtze River.

Figure 3. Average monthly mean differences in rainfall (a) amount (units: mm d\(^{-1}\)) and (b) frequency (units: %) between Reg. 1 and Reg. 2 (solid line) and Reg. 3 and Reg. 2 (dashed line) during 1961–2013. The gray line indicates zero.
In general, the rainfall amount and frequency deviations (Figure 3(b)) between Regs. 1 and 2 are consistent, and the rainfall frequency deviations are also large from March to May. However, the rainfall frequency also shows some distinct features. The rainfall frequency in Reg. 1 is always larger than that in Reg. 2, and the difference is the highest during April and the lowest in December. Although the rainfall amount is larger in Reg. 2 during summer, there is a smaller rainfall frequency, indicating a smaller daily rainfall intensity in Reg. 2. However, for the differences in rainfall amount and frequency between Reg. 3 and Reg. 2, these differences show a discrepancy from October to March. During the cold season, the rainfall amounts in Regs. 3 and 2 show fewer differences, but the Reg. 3 rainfall frequency is much larger than that of Reg. 2.

We selected March to May, which is when the differences between Reg. 1 and Reg. 2, as well as Reg. 3 and Reg. 2, are large for both rainfall amount and frequency. Figure 4 illustrates the rainfall amount (Figure 4(a)) and frequency (Figure 4(b)) averaged from March to May. The contrast among the three regions in Figure 4 is similar to that shown in Figure 2 but more obvious. The rainfall amount over Reg. 1 (3.46 mm d\(^{-1}\)) is approximately 5.2 times larger than that in Reg. 2, and 2.7 times larger than in Reg. 3. The values of Regs. 1 and 3 are close in terms of rainfall frequency, and the regional differences are also distinct.

To further analyze the rainfall characteristics that affect the regional rainfall differences, the occurrence and duration of rainfall events are shown in Figure 5. During March to May, approximately 1007 rainfall events occur in Reg. 3 (Figure 5(a)), and the greatest occurrence frequency of rainfall appears in Tongzi County, Guizhou Province (28.13°N, 106.83°E), which averages 1222 events during 1961–2013. The number of rainfall events is small over Reg. 1 (approximately 780), but the mean intensity (Figure 5(b)) and duration (Figure 5(c)) of rainfall are much stronger and larger in Reg. 1. Stations along the western edges of the Hengduan Mountains have a mean

Figure 5. The average (a) number, (b) rainfall intensity (units: mm d\(^{-1}\)) and (c) duration of rainfall events (units: d) from March to May during 1961–2013. The black boxes outline the three regions that are the main focus of this study. The white lines represent the Yangtze River.

Figure 4. (a) Average annual rainfall amount (units: mm d\(^{-1}\)) and (b) frequency (units: %) in March to May during 1961–2013. The black boxes outline the three regions that are the main focus of this study. The white lines represent the Yangtze River.
rainfall amount of approximately 18.0 mm d$^{-1}$ during each event, which is 2.1 (1.3) times that averaged over Reg. 2 (3). The rainfall events in Regs. 1 and 3 can last longer than those in Reg. 2, by approximately 1 day.

Previous studies have noted that rainfall occurring during the night through the morning is usually linked to large-scale circulation, whereas rainfall occurring in the afternoon is mainly caused by local solar forcing. Using the 12 hourly rainfall data, the distribution of days with rain occurring during the daytime (0800–2000 BJT) and nighttime (2000–0800 BJT) is shown in Figure 6. Although the rainfall during both day and night in Regs. 1 and 3 is greater than that in Reg. 2, the differences are much more obvious in the nocturnal rainfall. The average rainfall amounts in Reg. 2 are similar during the two periods, whereas nocturnal rainfall occupies a larger portion of the total rainfall in Regs. 1 and 3, especially in Reg. 3.

4. Summary and discussion

The rainfall features on the eastern and western edges of, and over the main body of, the Hengduan Mountains are distinct from other areas. The rainfall amount and frequency are much higher over the eastern and western edges than the rainfall amount and frequency observed over the mountains, especially during spring. This difference is partly due to the number of rainfall events and partly due to their durations. The differences are more obvious in the nocturnal rainfall than the daytime rainfall. The rainfall differences over the three regions could be affected by the large-scale environment.

In spring, the land–sea temperature gradient in the upper and middle troposphere reverses due to the shift in the Tibetan Plateau acting as a heat sink to a heat source (Yanai and Li 1994; Li and Yanai 1996). Similarly, the southwesterly wind appears and strengthens in the lower troposphere (Zhao et al. 2007). As shown in Li et al. (2011), the subtropical westerly jet over the southern margin of the Tibetan Plateau exists from December to May, and this jet reaches its maximum in April. Over the windward/ western side of the Hengduan Mountains, the strong westerly flow results in an upsliding wind (Figure 7). Combined with the large relative humidity (Figure 8), the orographic uplift produces ample rainfall in the western part of the mountains. However, after climbing over the mountains, the airflow subsides on the lee side. The maximum vertical velocity is greater than 0.3 Pa s$^{-1}$ at 600 hPa. Controlled by the sinking motion, the air temperature of the dry region can be increased by strong shortwave radiation. Similarly, the relative humidity is low over the Hengduan Mountains (53.3%). Combined with poor water vapor, the subsidence flow results in a low rainfall occurrence. On the eastern side of the mountains, easterly winds prevail near the surface east of 105°E. In spring, the easterly current is a cold airflow intruding from the northeast (Xie and Cheng 2004). The warm air from the mountains and the cold air in the east meet and form the Kunming quasistationary front, with rain developing east of the mountains, and the elevated topography is conducive to the stagnation of cold air, which limits the occurrence of rainy weather in the region east of 105°E (Duan, Li, and Sun 2002; Gu, Tian, and Pan 2006). The above effects of terrain and large-scale circulation on precipitation have been verified using numerical simulations (Li et al. 2011). Specifically, by removing the height of the western Hengduan Mountains, significant increases in the spring rainfall over the mountains were found. The lower elevation of the eastern highlands can also lead to an increase in rainfall over the dry region. The rainfall in the western and eastern areas of the mountains are

\[\text{Figure 6.}\] The ratio of the rainfall frequency during the (a) daytime (0800–2000 BJT) and (b) nighttime (2000–0800 BJT) to the total number of rainfall events from March to May during 1961–2013. The black boxes outline the three regions that are the main focus of this study. The white lines represent the Yangtze River.
weakened, which results in less rainfall differences among the three regions. The numerical sensitivity experiments in Wan and Wu (2007) also demonstrated the importance of the Tibetan Plateau to the formation of the spring persistent rains over South China; by removing or increasing the topography of the plateau, the southwesterly wind and rain over South China changed correspondingly.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was jointly supported by the National Key R&D Program of China [grant number 2018YFC1507603] and the

Figure 7. Longitude–pressure-level (units: hPa) section of (a) meridional winds (stream lines) and omega (shaded) and (b) zonal winds (shaded) averaged between 28°N and 35°N from March to May during 1961–2013. The black areas present the topography and the green horizontal lines present three target regions.

Figure 8. The average relative humidity (units: %) from March to May during 1961–2013. The black boxes outline the three regions that are the main focus of this study. The white lines represent the Yangtze River.
National Natural Science Foundation of China [grant number 41875112 and 41675075].

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