Characteristics of Cold Season Rainfall over the Yungui Plateau

JIAN LI AND RU Cong YU

State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China

(Manuscript received 10 September 2013, in final form 24 February 2014)

ABSTRACT

The climatic features of the distinctive cold season precipitation over the Yungui Plateau of China and the corresponding circulation background are investigated. From daily rainfall data observed with a high-density station network, it is found that the highest rainfall frequency in southern China during November–February appears over the Yungui Plateau. The rainfall intensity in this region is fairly low, and there is no remarkable rainfall-amount maximum. In comparison with the rainfall in southeastern China, the precipitation over the Yungui Plateau is more concentrated in weak events, with 85.9% of rainfall days having daily precipitation amounts of less than 3 mm. By regressing the circulation field on the rainfall frequency index, a favorable climatic background for high rainfall frequency is explored. In high-rainfall-frequency years, the surface wind exhibits southwesterly wind anomalies west of 104°E and cold air penetrates from the north on the eastern side. These two branches converge on the eastern edge of the Hengduan Mountains. In the lower troposphere, southwesterly winds prevail and anomalous water vapor fluxes converge over the Yungui Plateau. In the middle and higher troposphere, the westerly zonal wind strengthens and leads to an anomalous divergence. These dynamic and moist conditions contribute to the formation of clouds and precipitation. The northward- and eastward-facing slopes of the Yungui Plateau uplift the shallow, cold air carried by the northerly and easterly winds, and the terrain effects trigger the precipitation process. The low temperature and small specific humidity over the Yungui Plateau modulate the rainfall intensity to a low level.

1. Introduction

Geographically situated on the southeastward extension of the Tibetan Plateau (Fig. 1a), the Yungui Plateau of China rises roughly 1000–2500 m above sea level (Fig. 1b). The western part of the Yungui Plateau is connected to the Hengduan Mountains, a series of high north–south ridges (higher than 3500 m) and deep river-carved gorges. The surface elevation decreases to lower than 500 m to the east of the Yungui Plateau. Thus, the Yungui Plateau is a transitional area from the high mountains in the southeastern corner of the Tibetan Plateau to the eastern hilly and plains region. Corresponding to the distinct terrain features, the climate patterns on the western and eastern sides of the Yungui Plateau are also different. In the central part of the Hengduan Mountains, the year can be divided into distinct arid (November–April) and rainy (May–October) seasons. Most of the rainfall amount and its frequency is concentrated in the rainy season and is controlled by the southwesterly summer monsoon. In contrast, severe and long-lasting dry spells occur in the arid season, especially in early spring. Li et al. (2011) stated that the westerly flow along the southern edge of the Tibetan Plateau subsides on the leeward side of the high ridges at the western part of the Hengduan Mountains, suppressing precipitation and increasing the surface air temperature. The dry spells are regionally dependent, and most of them are confined west of 104°E. In the eastern hilly and plains region, there is a pronounced rainy period in spring, known as spring persistent rains. Tian and Yasunari (1998) stated that the thermal contrast between the Indo-China Peninsula and the western North Pacific is the main reason for the spring persistent rains. Wan and Wu (2007) argued that the mechanical and thermal effects of the Tibetan Plateau play an essential role in the formation of the spring rainfall in southeastern China. From early summer, with the onset of the mei-yu (the East Asian rainy season), this region is controlled by the rainfall belt of the East Asian summer monsoon (Tao and Chen 1987). Most works on the East Asian summer monsoon have focused on the region east...
of 110°E. Although the climatic features on both the western and eastern sides of the Yungui Plateau have been explored, there are fewer studies on the regional characteristics between 104°E and 110°E.

A principal component analysis was performed on the climatological mean annual cycle of the number of days with rain in each five-day period. The first empirical orthogonal function (EOF) mode accounts for 62.9% of the total variance, and its spatial pattern and time series are shown in Figs. 2a,b. This dominant mode is characterized by positive values over most of southern China. Large values are found in the Hengduan Mountains (west of 104°E) and the southeastern coastal region (south of 24°N and east of 110°E). The corresponding time series exhibits positive (negative) values from March to September (October–February), which indicates that there are distinct high (low) rainfall frequencies in the warm (cold) seasons in the Hengduan Mountains and the southeastern coastal region. In contrast to these two regions, the minimum value in Fig. 2a is found over the Yungui Plateau. The annual cycle of rainfall frequency over the Yungui Plateau is not closely related with the wet summer–dry winter pattern, and it has certain unique features. To reveal the diversity of the rainfall frequency in the annual cycle, Fig. 2c presents the standard deviation of the climatological pentad rainfall days, which has a pattern similar to that of the first EOF mode. Between the large values in the Hengduan Mountains and the southeastern coastal region, the smallest annual variation of rainfall frequency is located over the Yungui Plateau. This peculiar feature indicates that there are a considerable number of rainfall events even in winter.

In winter, the Yungui Plateau is controlled by the cloudy and rainy weather systems east of the north-
south-oriented Kunming quasi-stationary front. The cold air from the north and the westerly wind flowing around the southern edge of the Tibetan Plateau converge over the Yungui Plateau and lead to the formation of the Kunming quasi-stationary front in cold seasons (Yang et al. 1960). In approximately half of the days during November–April, this front can be found around 103.5°–104°E and is characterized by sharp differences in the amount of cloud and rainfall (Duan et al. 2002). The formation, structure, and influence of the Kunming quasi-stationary front have been discussed (Egger and Zuyu 1992; Du et al. 2007; Qian and Fu 2010). However, most of the previous research efforts were based on case studies or the composite of several typical processes and the data they used had fairly low spatial resolution. Since the Yungui Plateau is characterized by complex topography, the meteorological elements change sharply from place to place and the representative range of each weather station is much smaller than that in the plains region. Therefore, a set of long-term station observation data with high spatial resolution is used in this study to explore and understand the climatic features of the cold season precipitation over the Yungui Plateau. The climatic background for the winter rainfall is also discussed. Additionally, the high-resolution data enable a detailed consideration of the influence from the complex topography.

The remainder of this paper is organized as follows. Section 2 gives a brief description of the datasets and methods used in this study. Section 3 depicts the major characteristics of rainfall during November–February (NDJF). The corresponding climatic background is presented in section 4. A short summary is given in section 5.

2. Data and methods

The precipitation dataset used in this study was obtained from the National Meteorological Information Centre of the China Meteorological Administration. This dataset contains daily rain gauge records from 1954 to 2007. These precipitation data have undergone strict quality control. The quality testing consists of a climatological limit value test, a station extreme value test, and an internal consistency test. The analysis was restricted to the period 1966–2005 to avoid biases caused by missing data. Considering that even drizzle can cause severe problems in freezing winter weather, a day with a trace of rain (rainfall < 0.1 mm) recorded is taken as a rainy day in this study. The locations of the rain gauge stations are marked by dots in Fig. 1. The dense distribution of stations over the Yungui Plateau enables detailed spatial patterns to be identified in the complex topography. The daily records of surface wind, surface air temperature, and total cloud amount from stations in the national climatic reference network and national weather surface network of China were used. The radiosonde data (zonal and meridional wind from the surface to 200 hPa) at Guiyang (marked by a red triangle in Fig. 1a) and the National Centers for Environmental Prediction–National Center for Atmospheric Research 40-Year Reanalysis dataset (Kalnay et al. 1996; specific humidity and zonal and meridional wind at 850 hPa) were also analyzed to assess changes in the troposphere.
In this work, each year is subdivided into 73 pentads. The pentad (5 day) data are calculated to study the annual cycle of precipitation since they have less high-frequency noise than do the daily data and can present more details in seasonal and subseasonal variations than can the monthly data. The frequency is presented as the number of rainfall days in a certain period of time. For example, “pentad rainfall days” refers to the number of rainfall days per pentad, and “NDJF rainfall days” refers to the number of rainfall days during November–February. The rainfall amount is calculated by accumulating all the rainfall in a certain period, such as NDJF. The rainfall intensity (mm day\(^{-1}\)) is obtained by dividing the total rainfall amount by the number of rainy days.

3. Cold season precipitation

Figures 3a–c, respectively, show the climatological rainfall days, amount, and intensity during NDJF (1966–2005). A striking feature of Fig. 3a is the high days center over the Yungui Plateau. Forty-eight stations in this center reported rainfall on more than 70 days in NDJF, and 2 stations recorded more than 90 rainy days. Nevertheless, there is no corresponding rainfall amount maximum. As shown in Fig. 3b, there are two rainfall maxima: one is located south of 30°N and east of 110°E (hereafter referred to as the eastern center) and the other on the western edge of the Hengduan Mountains (west of 100°E). Between these two centers, the Yungui Plateau receives approximately 120 mm of rainfall in NDJF. From the distribution of the rainfall days and amounts, it can be deduced that the precipitation over the Yungui Plateau is relatively weak. In both the southeastern and western rainfall centers, the rainfall intensity exceeds 5 mm day\(^{-1}\), whereas over the Yungui Plateau the intensity is less than 1.5 mm day\(^{-1}\) (Fig. 3c). High frequency and low intensity are two key features of the Yungui Plateau rainfall.

To reveal the intensity-related rainfall structure, which can reflect more detailed characteristics of precipitation, all NDJF precipitation data for the period 1966–2005 were binned in 1 mm day\(^{-1}\) increments. The accumulated rainfall days and amount averaged over 25°–30°N are shown in Fig. 4. As rainfall intensity increases, the rainfall frequency decreases sharply (Fig. 4a). The highest frequency is found for rainfall lighter than 1 mm day\(^{-1}\) between 103° and 109°E, which exceeds 1500 days. The frequency peak remains over the Yungui Plateau for rainfall weaker than 3 mm day\(^{-1}\). For precipitation stronger than 5 mm day\(^{-1}\), the frequency peak is shifted eastward and is located east of 108°E. Figure 4b illustrates the distribution of the accumulated rainfall amount against intensity and longitude. There are two separate rainfall amount maxima: one between 104° and 108°E, with a concentration of light precipitation (less than 3 mm day\(^{-1}\)), and the other
east of 108°E, with a rainfall intensity of 5–10 mm day\(^{-1}\). Although in Fig. 3b the Yungui Plateau rainfall is not significantly partitioned from the eastern center, it has a distinctive intensity-related structure that is disparate from the precipitation in the surrounding regions.

Focusing on the rainfall over the Yungui Plateau, the 48 stations at which the number of NDJF rainfall days surpasses 70 were selected for further analysis. The locations of these stations are shown in Fig. 3a. Most of these locations lie on the Yungui Plateau, to the east of the Hengduan Mountains, and to the south of the Sichuan basin. The climatological mean annual cycles of the pentad rainfall days at these 48 stations are presented in Fig. 5 (gray thin lines). All of the gray lines exhibit similar annual cycles, and there is little diversity among different seasons. The average of the 48 stations (thick black line) is nearly flat throughout the year. The maximum and minimum values are 3.9 and 2.7 days per pentad, respectively. The difference between the mean of NDJF and the mean over the rest of the year (March–October) is only 0.3 days per pentad. For comparison, the annual cycles of rainfall days averaged over the surrounding regions are also shown. The blue line is for the region to the west of the Yungui Plateau (24°–28°N, 100°–103°E), which features low rainfall days in NDJF. The red line is for the eastern center (25°–30°N, 114°–120°E) as a rainfall amount maximum. The vertical bars in Fig. 5 represent the standard deviation among stations in each region. These three station groups show similar bar lengths, which indicate that the amounts of spread among the data in the three regions are comparable. The western region, which is located in the central Hengduan

---

**Fig. 4.** The distribution of 1966–2005 accumulated NDJF rainfall (a) days and (b) amount (mm) averaged over 25°–30°N as a function of rainfall intensity (mm day\(^{-1}\)).

**Fig. 5.** The annual variation in the rainfall frequency. The thin gray lines are for stations at which the number of climatological rainfall days exceeds 70 in NDJF, and the thick black line represents their mean. The blue line is for the regional mean to the west of the Yungui Plateau (24°–28°N, 100°–103°E), and the red line is for the regional mean to the east of the plateau (25°–30°N, 114°–120°E). The vertical bars denote the standard deviation among stations at each pentad.
Mountains, exhibits a strong seasonal variation in rainfall frequency. The blue line peaks in July (4.1 days) and reaches its minimum in December (0.7 days), presenting a much larger amplitude than the black line. The difference between the NDJF and March–October means reaches 1.8 days per pentad in this region. The rainfall frequency of the eastern center is lower than the mean value of the 48 stations throughout the year except for several pentads in early spring. The distance between the red and the black lines is narrow in spring and summer and then increases after October. The minimum frequency of the eastern center (1.6 days) is lower than that of the 48-station mean, indicating a relatively stronger seasonal variation. In NDJF, the mean rainfall frequencies of stations in both the western region and the eastern center are lower than the mean values of the 48 stations. The differences between the Yungui Plateau and the western region, and between the Yungui Plateau and the eastern center, have been examined using the Student’s t test and are statistically significant at the 0.05 level. The rainfall frequency over the Yungui Plateau is different from both the upstream high-mountain region and the downstream hilly and plains region, and the regional difference is most pronounced in NDJF.

Similar to Fig. 4, Fig. 6 also depicts the rainfall structure related to the daily intensity, but for the average of the 48 stations and the eastern center. As shown in Fig. 6a, the number of accumulated rainfall days drops sharply as the rainfall intensity increases, and most of the rainfall events are concentrated on the weak side. The black line (48-station mean) is steeper than the gray line (eastern center) for an intensity of less than 3 mm day\(^{-1}\). The weak rainfall events (with an intensity of less than 3 mm day\(^{-1}\)) account for 85.9% (61.6%) of the total rainfall days at the 48 stations (eastern center). The accumulated rainfall amount is shown in Fig. 6b, and the two lines peak at different intensity values. The 48-station mean reaches its maximum (611.2 mm) in the 1–2 mm day\(^{-1}\) intensity bin. The weak rainfall events contributed 31.1% of the total rainfall amount at these stations. The distribution of rainfall in the eastern center is displaced more toward the high-intensity side, with a peak of 455.4 mm at 6–7 mm day\(^{-1}\). Only 8.2% of the rainfall comes from precipitation events weaker than 3 mm day\(^{-1}\).

4. Climatic background

Figure 7a shows the NDJF rainfall days at the 48 stations (gray lines) and their average (black solid line) from 1966 to 2005. These stations have a consistent interannual variation. The correlation between each station and the average of the remaining 47 stations was calculated. The 48-station mean value of the correlation coefficients is 0.75, and only 7 stations have values less than 0.60. Thus, the black line can adequately represent the interannual variation in rainfall frequency at these stations. The standardized series of this black line is defined as an index to reflect the NDJF rainfall days over the Yungui Plateau. To reveal the climatic background for high NDJF precipitation frequency, variables are linearly regressed on the rainfall frequency index via the least squares method. The linear regression coefficients between circulation fields and the frequency index show...
the anomalies associated with a unit anomaly in the standardized rainfall days series. Figures 7b–d show the surface wind, total cloud amount, and surface air temperature, respectively, and all three variables come from the surface-station network. In the regressed surface wind field (Fig. 7b), two branches of air masses converge along the eastern edge of the Hengduan Mountains, from roughly 30° N, 102° E to 23° N, 105° E. To the west of the convergence line, southwesterly wind anomalies dominate the high-mountain region, supplying warm and moist air. In contrast, on the eastern side, northerly wind anomalies bring cold air. Figure 7c shows the total cloud amount anomalies regressed on the rainfall frequency index. In the high-rainfall-frequency years, cloud amount significantly increases in most of southern China, except over the Hengduan Mountains. The maximum cloud anomaly center is located over the Yungui Plateau, with positive values larger than 4.5%. Climatically, the Yungui Plateau and the regions east of it are covered by deep middle level stratus clouds, which are related to the divergence at 600–500 hPa and have strong negative cloud radiative forcing (Yu et al. 2004). Both the cold advection by northerly wind and the negative cloud radiative forcing can lead to local cooling. Figure 7d presents the temperature anomalies associated with high rainfall frequency. Cold anomalies dominate over most of southern China, and minima lower than −0.45°C are found over the Yungui Plateau. To the north of the high-rainfall-frequency region, the cooling is also strong and significant, which shows the tracks of the cold air.

The water vapor transportation in the lower troposphere derived from the reanalysis data is regressed on the rainfall frequency index (Fig. 8a). The anomalous water vapor flux extends from the Indo-China Peninsula and surrounding seas to southern China, and there is a significant convergence center of water vapor flux over the Yungui Plateau. The maximum value appears at 25° N, 105° E, and the significant converging region extends from 20° to 27.5° N and from the eastern edge of the high topography (higher than 1500 m is shaded black) to 107.5° E. To reveal the vertical structure of the circulation anomalies associated with the precipitation events, the wind profile over Guiyang is also regressed on the rainfall frequency index. At the near-surface level, the negative value of the meridional wind (red line in Fig. 8b) signifies the northerly wind anomalies. The sounding of Guiyang in the lowest level is representative of the region to the east of the convergence zone shown in Fig. 7b. This northerly flow is confined to the lowest layer, and the anomalous meridional flow shifts to a southerly wind in the lower troposphere. The zonal wind exhibits positive anomalies at 850 hPa, and the anomalous westerly flow dominates the middle and upper troposphere. Large positive values of the regressed zonal wind at 300–200 hPa indicate that the cold season rainfall days over the Yungui Plateau might be
related to the Asian subtropical jet. The westerly jet stream over subtropical East Asia is an important atmospheric circulation system, which is intimately associated with many features of the surface weather and climate. During the cold season, the subtropical jet at 200 hPa appears around 30°N, extending from North Africa throughout the Asian continent, as shown by the shading in Fig. 9. The jet axis is narrow and is located to the south of the Tibetan Plateau (Schiemann et al. 2009). The 200-hPa zonal wind anomalies regressed on the rainfall days index are shown in Fig. 9 by contours. In years with high cold season rainfall days, the subtropical jet from the Arabian Peninsula to the Yungui Plateau is significantly strengthened. Positive zonal wind anomalies are found along and immediately south of the climatological jet stream, with the maximum positive anomalies located at 25°N, 75°E. This connection between the rainfall-days index and the subtropical jet exhibits the large-scale climate background for the cold season rainfall over the Yungui Plateau. Yao and Li (2013) found that the intensity of the winter East Asian subtropical jet is significantly correlated with the surface air temperature in China. In winters with stronger subtropical jet, the temperature downstream of the Tibetan Plateau is lower than normal. Xin et al. (2010) suggested that the East Asian subtropical jet can influence the snowfall over the Tibetan Plateau. The intensified winter subtropical jet is favorable for the deepening of the India–Myanmar trough in the lower troposphere due to the blocking effect of the Tibetan Plateau. The enhanced southwesterly wind in front of the India–Myanmar trough transports more moisture from the Bay of Bengal, leading to more precipitation over the eastern Tibetan Plateau in winter. Also, the stronger westerly winds associated with the intensified winter subtropical jet can lead to middle-level divergence to the southeast of the Tibetan Plateau through the frictional effect of the huge plateau (Yu et al. 2004).

Overall, the favorable circulation field for high rainfall frequency over the Yungui Plateau includes the following factors: a strengthened westerly wind at the middle and upper troposphere, which are favorable for the middle-level divergence over the Yungui Plateau; southwesterly and northerly winds converging at the
surface level (these first two factors ensure the dynamic conditions for the formation of clouds and precipitation); a prevailing southwesterly stream in the lower troposphere transporting water vapor to the Yungui Plateau; and the effect of the local topography, which plays an important role in the rainfall process. The complex and high topography blocks the cold air penetrating from the north, and the orographic uplift on the eastern and northern sides of the highlands triggers weak precipitation over the Yungui Plateau. As shown in Fig. 10, the highest frequency along 27.5°N occurs at approximately 1500 m, just on the edge of the Hengduan Mountains. The number of rainfall days drops quickly westward as the surface elevation exceeds 1500 m because the shallow cold current cannot get over and invade the high Hengduan Mountains. East of 106°E, it can be found that each frequency peak is located on the eastern side of a local highland. As shown in Fig. 3a, Most of the high-rainfall-frequency stations are located on the eastern or northern sides of the high topography, the windward flank for the cold air. The distribution of the rainfall frequency and the topography confirms the importance of the terrain effects. The proper height and the just-right slope on the northern and eastern sides make the Yungui Plateau vulnerable and sensitive to the cold air.

Several factors provide favorable conditions for rainfall occurrence. But what limits the intensity of precipitation over the Yungui Plateau? To discuss this question, the thermal and moisture conditions over the Yungui Plateau and the eastern region with higher rainfall intensity are compared. Figure 11 exhibits the meridionally averaged (26°–28°N, crossing through the maximum of NDJF rainfall days) surface air temperature (black solid line), relative humidity (gray solid line), and specific humidity (dashed line). The climatological NDJF temperature increases rapidly from 104° to 120°E, while the relative humidity shows no significant zonal changes and simply oscillates slightly around 80%. Correspondingly, as the saturation moisture content increases as a consequence of the increased temperature, the moisture-holding capability of the atmosphere increases from west to east, which is consistent with the zonal distribution of the specific humidity. The weak rainfall region (104°–108°E) has low temperature (6.5°C) and small specific humidity (5.6 kg m⁻²). In contrast, the region with stronger rainfall (115°–120°E, as shown in Fig. 3c) has much higher temperatures (10.2°C) and larger specific humidity (6.4 kg m⁻²). Poor thermal and moisture conditions might be one reason responsible for the weak rainfall over the Yungui Plateau.

5. Summary and discussion

This paper documents the climatic features of NDJF rainfall over the Yungui Plateau, and the corresponding climate background is analyzed. With a focus on characteristics distinct from the surrounding regions, this study enriches our knowledge on the climate over the southeastern extension of the Tibetan Plateau. Our major conclusions are summarized below.

(i) The annual variation in rainfall frequency over the Yungui Plateau is the smallest in southern China.
(ii) The number of NDJF rainfall days over the Yungui Plateau is the highest in southern China, but the rainfall intensity is low. The Yungui Plateau cannot be distinguished from the surrounding regions only by rainfall amount.
(iii) At high-rainfall-frequency stations, most rainfall events have low intensity. The weak rainfall with an intensity less than 3 mm day⁻¹ accounts for 85.9% (31.1%) of the frequency (amount), which is much larger than that in the eastern center.
(iv) The favorable circulation field for high rainfall frequency includes near-surface convergence, high
low-level water vapor transport, and strong westerly winds in the middle and upper levels. 

(v) The precipitation is significantly influenced by the topography. The highlands on the northern and eastern sides of the Yungui Plateau uplift the shallow cold currents and cause the formation of clouds and weak precipitation. 

(vi) The weak rainfall intensity is related to the low temperature and small specific humidity. The cold season rainfall over the Yungui Plateau is closely related to the Kunming quasi-stationary front, which is an important climatological feature of the cold season circulation to the southeast of the Tibetan Plateau. The high-rainfall-frequency region is located to the east of the Kunming quasi-stationary front, and the largest gradient is along the north–south-oriented front (Fig. 3a). The number of NDJF rainfall days to the west of the Kunming quasi-stationary front is less than 30 days, while there are more than 70 rainfall days to the east of the front. In high-rainfall-frequency years, the increase of cloud amount to the east of the front is much higher than that on the western side of the front. The sharper contrast along the front indicates that the Kunming quasi-stationary front might be more frequent, more persistent, and more intense so as to produce more rainfall events on its eastern side. The specific relation between the Kunming quasi-stationary front and the features of the rainfall over the Yungui Plateau will be explored in further research efforts.

Acknowledgments. This research was supported by the Major National Basic Research Program of China (973 Program) on Global Change under Grant 2010CB951902, the National Natural Science Foundation of China under Grants 41221064 and 41322034, the Basic Scientific Research and Operation Foundation of the CAMS (Grant 2013Z004), and the Jiangsu Collaborative Innovation Center for Climate Change.

REFERENCES


