Early Spring Dry Spell in the Southeastern Margin of the Tibetan Plateau

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Abstract

The climatic features of the distinctive early-spring dry spell in the southeastern margin of the Tibetan Plateau and the relationship between this dry spell and topographic forcing are investigated. The results show that the early-spring dry spell is characterized by the lowest relative humidity and highest evaporation in the year and by an extremely low amount of rainfall in March and April. The dry spell is a regional phenomenon, as centers of high relative humidity and large rainfall amounts are located to both the east and west of the dry region. In the major dry region, more than 80% of the days in March and April are “dry” days, during which the daily precipitation amounts to no more than 0.1 mm. The mean duration of a dry period between two consecutive rainfall events is found to be 7 days. Further analyses indicate that the relationship between the prevailing westerly flow and the topographic conditions plays an important role in the formation of the dry spell. Strong orographic uplift occurs as the westerly wind flows over the north-south-oriented mountain ranges to the west of the dry region; this in turn causes heavy rainfall over the windward side. After flowing over the mountains, the air subsides over the dry region on the leeward side, suppressing precipitation and increasing the surface air temperature. On the basis of sensitivity experiments carried out using a regional climate model, the role of the topographic conditions in modulating the local climate is confirmed. Reduction in the height of the western mountains as well as lowering of the elevation of the eastern highlands can lead to significant increases in the early-spring rainfall over the dry region.

1. Introduction

In early spring, severe dry spells occur in the southeastern margin of the Tibetan Plateau. Drought is the most serious and frequent climatic disaster in this area, and it poses a major threat to agriculture and ecosystems. Between 1901 and 1997, winter and spring droughts occurred 75 times, and there were 13 years with severe droughts (Duan et al. 2000). From autumn 2009 to spring 2010, this region experienced drought of a severity that is observed only once in 50 years. Crops grown over thousands of hectares of land were destroyed, and millions of people suffered from short-
Fig. 1. The surface elevation (shaded, 100 m) over southern China. The major dry region is marked by a rectangle, and the locations and names of the nine stations are labeled. The five stations located in the dry region are marked by squares. The two stations to the west (east) of the dry region are marked by circles (triangles).

The rainfall amount decreased to about 50% of the average climatic value for the given period, the lowest level in the last half century. The central part of the Hengduan Mountains (about 24–28°N and 100–103°E, marked by a rectangle in Fig. 1) is climatologically dry in early spring. As shown in Fig. 1, the terrain along the southeastern margin of the Tibetan Plateau is rather complex. Generally, the topography descends from north (over 4000 m in the main body of the Tibetan Plateau) to south (around 1000 m). The dry region is at a relatively low altitude. To the west of the dry region, there are a series of steep, north-south-oriented parallel ridges, which form a huge barrier (higher than 3500 m). To the east of the dry region, the terrain is elevated to the height of more than 2000 m. Owing to this complex topography, the climate along the southeastern margin of the Tibetan Plateau is strongly region-dependent. In sharp contrast, there is a strong rainfall center at the west of the dry region. The climatological rainfall amount in March exceeds 220 mm at Gongshan and Fugong (marked by circles in Fig. 1) (Lu et al. 2008). The east of the dry region receives rainfall in spring as well. Spring Persistent Rains (SPRs) are the well-known synoptic and climatic phenomenon observed in southeastern China from pentad 12 to pentad 26. The large-scale circulation associated with SPRs has been analyzed, and the related mechanisms have been discussed (Tian and Yasunari 1998; Wan and Wu 2007). Tian and Yasunari (1998) proposed that the thermal contrast between the Indochinese Peninsula and the western North Pacific, to the east of the Philippines, is responsible for SPRs. Wan and Wu (2007) argued that the mechanical and thermal effects of the Tibetan Plateau are the essential climatic causes of SPRs formation. Although the SPRs occurring in the region east of 110°E have been explored, very few studies have focused on the severe early-spring dry spells occurring in the region west of the rainy region. Xie and Cheng (2004) proposed that the high north-south-oriented mountains to the west of the dry region are responsible for the drought. Ma and McConchie (2001) briefly reviewed the mechanisms underlying the formation of the dry-hot valley in southwestern China, for which the major factors include the atmospheric circulation system, the mountain-valley system and foehn effect, and human activities. They also stated that most discussions and analyses regarding the evolution of dry-hot conditions are hypothetical. Even now, the features of the climatic dry spell have not been analyzed systematically, and the factors responsible for this dry spell have not been adequately verified.

As a part of the Asia-Pacific monsoon systems, the dry region belongs neither to the Indian summer monsoon nor to the East Asian summer monsoon region (Wang and Lin 2002). The Hengduan Mountains, which have certain peculiar features, act as a transitional zone between these two monsoon components. By understanding the key processes governing the local climate of this dry region, we can enrich our knowledge of monsoon systems. The dry region is also located in a major water vapor path, via which the southwesterly wind brings moisture from the Arabian Sea and the Bay of Bengal to eastern China. This water vapor transport branch makes a significant contribution to the rainfall downstream of the Tibetan Plateau in spring and summer (Simmonds et al. 1999; Zhou and Yu 2005; Zhang et al. 2009). Therefore, analysis of the specific climatic features in this region is of great importance for understanding the variation in the moisture conditions across eastern China. Some Atmospheric General Circulation Models (AGCMs) show large biases when used for simulating the climate on the eastern periphery of the Tibetan Plateau (Yu et al. 2000); this is partly because they have relatively coarse horizontal resolution and hence cannot represent complex terrain characteristics. Therefore, revealing the characteristics of the local climate in this area can also help validate and improve the currently used numerical models.
The objective of this study is to describe the climatic features of the dry spell and to study the related mechanisms. We compare the climatic features of the dry region to those on the western and eastern sides of this region by taking into account the complex topography and the strong localization of the dry spell. Then, we identify the possible mechanisms responsible for the dry spell and carry out two numerical sensitivity experiments to confirm the proposed mechanisms. The remainder of this paper is organized as follows. Section 2 gives a brief description of the data sets, analysis methods, and numerical model used. Section 3 describes the analysis of the climatic features of the early-spring dry spell. Section 4 presents the influence of topographic conditions on the dry spell. The results of the numerical experiments are presented in Section 5, and the validity of the proposed topographic influences is shown. Finally, a short summary is given in Section 6.

2. Data, methods, and model description

The surface climate data used in this study were obtained from the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). The data contains the daily records from stations in the national climatic reference network and national weather surface network of China from 1961 to 2004. This data set has undergone strict quality control. The quality testing consists of a climatological limit value test, a station extreme value test, and an internal consistency test. In this study, the relative humidity, surface evaporation, and rainfall values were used. The daily data were averaged to give the pentad mean, and the climatological annual cycle was constructed for the period from 1961 to 2004. To investigate the related large-scale circulation, we also used reanalysis data. The zonal wind and vertical velocity data were taken from the Japanese 25-year ReAnalysis (JRA-25) (Onogi et al. 2007) for the period from 1979 to 2004 and from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al. 1996) for the period from 1961 to 2004.

The number of dry days and the dry spell duration are calculated in order to quantify the severity of the dry spell. In this study, “dry” days are defined as days during which no more than 0.1 mm of rainfall is recorded. The percentage of dry days in the total observation period can reflect the overall nature of the dry climate. The “duration” of a dry period is defined as the number of dry days between two consecutive rainfall events (with a 0.1 mm/day threshold). The mean duration of the dry spells is calculated by averaging the durations of all the dry periods; this mean duration indicates the climatic persistence of the dry spell.

To obtain a suitable resolution for the complex and steep topography in the southeastern margin of the Tibetan Plateau, we used the Climate version of Advanced Regional Eta-coordinate Model (CREM) in this study. Shi et al. (2009) described the structure of CREM in detail, and evaluated its simulation of the summer climate over eastern China. Using the eta (η) coordinate (Mesinger 1984) and constructing the topography as step-like mountains, the CREM shows certain advantages in simulating the forcing of the steep orography such as that on the eastern edge of the Tibetan Plateau. The Biosphere-Atmosphere Transfer Scheme version 1e (BATS1e) (Dickinson et al. 1993) and an advanced radiation package (Edwards and Slingo 1996; Sun and Rikus 1999) are used in CREM to make it suitable for climate research. Shi et al. (2009) stated that the CREM can adequately describe the summer climate over eastern China, reasonably reproducing features such as the climatological distribution of precipitation and the circulation field, the interannual variation of precipitation, and the intraseasonal shift of the major rain belt. In this study, the model domain was 13–53°N and 87–140°E. The horizontal resolution was set to 37 km, and there were 36 vertical levels from the model bottom to 10 hPa. The initial conditions and lateral boundary conditions were generated from the NCEP reanalysis data at 6-h intervals (Kalnay et al. 1996). The weekly Optimally Interpolated Sea Surface Temperature data (Reynolds et al. 2002) were interpolated in space and time to supply sea surface temperature forcing.

3. Early-spring dry spell in the southeastern margin of the Tibetan Plateau

Figure 2 shows the spatial distribution of the phase (arrow at each station) and amplitude (shading) of the annual cycle of relative humidity (a) and evaporation (b). The phase indicates the month in which the annual minimum (maximum) relative humidity (evaporation) occurs. The extreme month is represented by an arrow on a circular 12-month dial clock. The annual amplitude of the relative humidity (evaporation) is defined as the difference between the value of the annual minimum (maximum) month and the annual mean. The maximum annual amplitudes of relative humidity and evaporation occur in the southeastern margin of the Tibetan Plateau, which indicates that there are strong seasonal variations in this area. As shown by the arrows in Fig. 2a, at 12 stations out of the total of 16 stations located in the central Hengduan Mountains (marked by a rectangle in Fig. 1), the annual lowest relative humid-
Fig. 2. (a) The month in which the annual minimum relative humidity occurs is represented by arrows on a circular 12-month dial clock and the numbers in the clock denote the months. The shading represents the amplitude of the annual relative humidity (unit: %). The major dry region is marked by a rectangle. (b) The arrows represent the month in which the annual maximum evaporation occurs. The shading represents the amplitude of the annual evaporation (unit: mm/day). The solid grey line shows the 2000-m elevation contour line.

To further reveal the annual cycle of the relative humidity in the southeastern margin of the Tibetan Plateau, we performed a principal component analysis on the climatic pentad mean data. The resulting spatial pattern and time series of the first empirical orthogonal function (EOF) mode are shown in Fig. 3. This dominant mode accounts for 81.0\% of the total variance. As shown in Fig. 3a, the first EOF is characterized by positive values over most of southwestern China, with very small negative values (absolute value less than 0.02) only over certain areas east of 105°E. The largest positive value is found in the central Hengduan Mountains, and the values decrease sharply to both the east and the west. The corresponding time series, shown in Fig. 3b, reveals the existence of distinct wet and dry seasons. The wet season starts from pentad 31 and ends in pentad 69. The time series is fairly flat, and no prominent
peaks are found in the wet phase. During the rest of the year, the relative humidity is comparatively low, reaching its annual minimum at pentad 15 (around the 12th to 16th March).

To give a comprehensive image of the moisture features over the early-spring dry region, Fig. 4 shows the interpentad variation of the relative humidity and evaporation at five stations (marked by squares in Fig. 1) located in the central Hengduan Mountains. The annual cycle of relative humidity (Fig. 4a) presents similar variation to the time series of the first EOF mode (Fig. 3b), with the driest period around early spring, and the wettest period in summer. As shown in Fig. 4b, the evaporation starts to increase dramatically in winter, and reaches its annual maximum shortly after the lowest point of relative humidity. For both relative humidity and evaporation in the central Hengduan Mountains, the largest departures from the annual mean occur in spring. Figure 4c presents the interpentad variation of precipitation at the five stations. From January to the end of April, the rainfall amount remains at a low level (below 2.5 mm/day). There is no significant change in precipitation during the transition from winter to spring, and the low-rainfall period persists until the end of April. The variations of relative humidity, evaporation, and rainfall indicate that the main period of the dry spell is from pentad 13 to pentad 22 in early spring. The climatological spatial distribution of rainfall from pentad 13 to 22 is shown in Fig. 5a. The early-spring arid climate
exhibits strong localization, with a rainfall amount averaged over the major dry region of only 0.6 mm/day. In contrast, the amount of rainfall increases significantly to both the east and the west of the dry region. There is a strong precipitation center, with a daily rainfall of over 8 mm, located around 150 km west of the major dry region. To the east of the narrow dry area, the rainfall amount exceeds 3 mm/day at 108°E. For comparison, Fig. 5b shows the annual mean rainfall amount. The zonal gradients of rainfall are much weaker on both the eastern and western sides. The annual mean precipitation amount averaged over the major dry region is 3.0 mm/day, which is much larger than that in early spring.

Figure 6a shows the percentage of dry days in March and April from 1961 to 2004. In the central Hengduan Mountains the percentage of dry days exceeds 80%, with the maximum at Huaping (90.48%). The percentage of dry days is much smaller in the surrounding regions. At Gongshan (Kaili), to the west (east) of the major dry region, the dry days account for only 24.18% (39.50%) of the total. The impacts of the dry spells depend largely on how long they persist. The mean duration of the dry spells is shown in Fig. 6b. In the major dry region the mean duration exceeds 7 days, and the longest mean duration of the dry spells is 13.3 days (at Huaping). The mean duration shrinks to less than 3 days on the western and eastern side of the central Hengduan Mountains. The dry spells of long duration should be given more attention because they are more likely to lead to severe drought. The number of dry spells with duration equal to or more than 10 days is also analyzed, and the results are shown in Fig. 6c. Unlike the distribution of the mean duration (Fig. 6b), the highest frequency is found in the southern part of the
Fig. 7. The annual cycle of zonal wind averaged over 90–100°E at 700 hPa (shaded) and 200 hPa (contour) (unit: m/s). The X-axis represents the pentad number. The zonal wind was taken from the NCEP/NCAR reanalysis data.

central Hengduan Mountains, where 65 such cases are recorded. In the surrounding regions, no dry spell of at least 10 days was recorded at Kaili, and only one case was noted at Guiyang and Gongshan in March and April between 1961 and 2004.

As shown in the above analysis, there are large gradients in relative humidity and dry spell features between the major dry region and surrounding areas, especially on the western and eastern sides of the dry region, where it is quite wet and rainy in early spring. The dry spell in the central Hengduan Mountains is a regional phenomenon, which might be caused by the relationship between the large-scale circulation and the complex topography.

4. Impact of topography on the early-spring drought

In the dry region, early spring is a special transition season with unique circulation features. In early spring, the Tibetan Plateau shifts from being a heat sink to being a sensible heat source (Yanai and Li 1994), which causes the reversal of the land-sea temperature gradient in the upper and middle troposphere (Yanai et al. 1992; Li and Yanai 1996; Qi et al. 2007). Accompanying the changes in thermal conditions, the southwestward wind appears and strengthens in the lower troposphere over southeastern China (Zhao et al. 2007), and the surface wind speed reaches its annual maximum in the southwestern margin of the Tibetan Plateau (Yu et al. 2009). As shown by the contours in Fig. 7, the 200-hPa zonal wind (derived from NCEP/NCAR reanalysis) upstream of the dry region is strong during winter and early spring. The subtropical westerly jet is located at the southern edge of the Tibetan Plateau, directly over the dry region, from December to April (Schiemann et al. 2009). In the lower troposphere (700 hPa), a strong westerly wind (greater than 8 m/s, shown by the shading in Fig. 7) persists from mid-winter to mid-spring. The 700-hPa zonal wind averaged over 24–29°N and 94–99°E reaches its annual maximum in pentad 16. Both the higher and lower levels of the troposphere present strong westerly winds, which blow to the Hengduan Mountains almost at right angles. Therefore, the blocking effect of the topography on the atmospheric circulation is intense in early spring.

The 24–28°N meridionally averaged vertical circulation of pentad 13–22 in the southeastern margin of the Tibetan Plateau is derived from JRA-25 reanalysis, and is shown in Fig. 8a. Over the windward side of the Hengduan Mountains, the strong westerly flow results in a branch of up-sliding current. This orographic uplift, which is favorable for precipitation, produces excessive rainfall in the west of the central Hengduan Mountains. Two stations located in this region (marked by circles in Fig. 1) show strong rainfall peaks in the early spring (two blue lines in Fig. 4c) that exceed 10 mm/day. The early-spring rainfall is closely related to the strength of the upstream zonal wind. The correlation coefficient between the 700-hPa zonal wind in March (averaged over 24–29°N and 94–99°E) and the March rainfall at the Gongshan station is 0.569 for the period from 1961 to 2004. Moisture from the Arabian Sea and the Bay of Bengal is the main source of water vapor for this early-spring rainfall center (Lu et al. 2008). The water vapor is carried eastward by the zonal wind, and a certain portion is blocked by the Hengduan Mountains.

After being lifted over the north-south-oriented mountains, the westerly flow subsides on the leeward side, around 100–103°E. The maximum vertical velocity exceeds 0.2 Pa/s at 600 hPa. Through a reduction in the rainfall amount and an intensification of surface evaporation, this steady sinking motion plays an important role in the formation of the early-spring dry spell. Although some water vapor is transported to this region by the westerly wind, the subsidence flow suppresses the wet convection, causing a very low rainfall amount. From 1961 to 2004, the daily rainfall in March at the Yuanmou station in the dry area is closely related to the vertical velocity at 600 hPa, and the correlation coefficient reaches 0.37. Meanwhile, the surface air temperature can be increased efficiently by the strong short-wave radiation in this cloudless region controlled by the sinking motion. The mean temperature of pentad 13–22 at Yuanmou (1120.6 m above sea level) is 22.6°C. This is significantly higher than the mean temperature at Kaili (12.7°C), which is located at a much lower al-
A high surface air temperature and low rainfall amount can lead to the low relative humidity. The relative humidity at Yuanmou correlates well with the vertical velocity derived from NCEP/NCAR reanalysis in the middle and low-level troposphere (shown in Fig. 8b). Stronger subsidence flow corresponds to a drier surface climate, and the maximum correlation coefficient exceeds $-0.5$ at 600 hPa. By changing the surface air temperature, the vertical velocity also modulates the evaporation. A higher surface air temperature strengthens the turbulent transport, and the kinetic energy of the free atmosphere can be transported to the surface layer more efficiently. Thus, the surface wind speed increases and the evaporation increases, further intensifying the early-spring dry spell. Another reason for the dry climate is the blocking of the westward cold air by the elevated topography to the east of the central Hengduan Mountains. As shown in Fig. 8a, an easterly wind prevails near the surface level east of 105°E. This current is a cold air flow intruding from the northeast (Xie and Cheng 2004). The warm air in the dry region and the cold air to the east of this region meet and form the Kunming Quasi-Stationary Front. Duan et al. (2002) show that the Kunming Quasi-Stationary Front is located at around 103.5–104°E with a north-south-oriented front line, which is characterized by the sharp differences in the amounts of rainfall and cloud between the Kunming and Guiyang stations. The elevated terrain to the east of the major dry region leads to the stagnation of the cold air flow, and limits the cloudy, rainy weather to the region east of 105°E (Gu et al. 2006). On the other side of the front, in the central Hengduan Mountains, it is sunny and cloudless, and the dry spell persists.

5. Sensitivity experiments performed using a regional climate model

Sensitivity numerical experiments are the effective way to evaluate the impact of different factors. We performed such experiments here to verify the idea that topographic forcing plays an important role in the formation of the early-spring dry spell.

5.1 Experiment design

In this study, one control run and two sensitivity experiments were performed. These were all two-month (February and March) simulations, which were integrated for each year from 1991 to 2000. The results in March, the typical early-spring period, were analyzed, and the integration in February was employed as a “spin-up” period. Figure 9a shows the control run model topography over the southeastern margin of the Tibetan Plateau. Comparing with Fig. 1, it is seen that the CREM can adequately represent the major topographical features in this region. The relatively low altitude in the central Hengduan Mountains and the el-
evated terrains on the western and eastern sides are resolved. Therefore, the CREM has the potential to describe the local orographic forcing in the target region. To validate the mechanisms presented in the previous section, we designed two sensitivity experiments. In the first sensitivity experiment (S1), the topography in the west of the major dry region was modified to weaken the influence of the western mountains. The maximum height in the area from 22°N to 28°N and from 98°E to 101°E was set at 2700 m, and the mountain ridges higher than 2700 m were removed, as shown in Fig. 9b. The second sensitivity experiment (S2) was designed to test the effects of the topography to the east of the central Hengduan Mountains. In the eastern region (22–28°N, 101–107°E), the topography exceeding 2000 m was cut off (Fig. 9c). Except for the topography, all other conditions in the experiments remained the same.

5.2 Results of numerical experiments

As an evaluation of the ability of the CREM to simulate the early-spring precipitation, Fig. 10 presents the observed (a) and simulated (b) the mean daily rainfall in March (1991–2000). According to the observation data, there are two rainfall centers in southern China. One rain belt is located at the south of 30°N and east of 105°E, and has been referred to as SPR (Tian and Yasunari 1998; Wan and Wu 2007). The other center is located at the west of 100°E and on the southern edge of the Tibetan Plateau. In this area, the climatic March rainfall at Gongshan reached 11.60 mm/day for the period from 1991 to 2000. Between these two precipitation centers lies the dry region that is the focus of our studies. Figure 10b gives the March rainfall simulated in the 10-year control experiment. For the rain belt in southeastern China, the CREM predicts its location fairly well, albeit with a larger rainfall amount. The CREM also simulates the strong rainfall center in southwestern China at the west of 100°E. In the central Hengduan Mountains, the rainfall amount is less than 2 mm/day and there is a significant dry area according to the CREM results. Comparison between Fig. 10a and 10b reveals that the CREM can reproduce the west-east-
Fig. 10. The mean daily precipitation for March during the period 1991–2000 for the station observation (a) and the CREM simulation (b). The contour interval is 1 mm/day. (c) The mean daily precipitation for March averaged over the central Hengduan Mountains (24–28°N, 100–103°E) for station observation (gray solid line) and CREM simulation (black dashed line). The major dry region is marked by a rectangle in (a).

oriented “wet,” “dry,” “wet” pattern reasonably well. Focusing on the dry region, Fig. 10c shows the March rainfall averaged over 24–28°N and 100–103°E. During the period from 1991 to 2000, the observed (gray solid line) and simulated (black dashed line) precipitation amounts exhibit a coherent interannual variability, with a correlation of 0.92. Although the CREM overestimates the rainfall amount in the central Hengduan Mountains with an average bias of around 0.58 mm/day, it reproduces the major rainfall characteristics in this region. Therefore, the CREM can be used to test the influence of the topography surrounding the major dry region.

The differences in the 10-year mean March precipitation between the sensitivity experiment S1 and the control run are shown in Fig. 11a. Reducing the height of the mountains to the west of the dry region leads to a significant decrease in precipitation on the western side of the Hengduan Mountains. The maximum rainfall change on the windward side of the mountain exceeds 5 mm/day. In contrast, with the lower barrier for the westerly wind, the rainfall amount in the dry region increases significantly. The mean daily rainfall in March averaged over 24–28°N and 100–103°E increases by 0.72 mm/day (around 68.57% of the climatic amount). These rainfall differences indicate that the high mountains between 98–101°E are responsible for the heavy rainfall in southwestern China, and can suppress precipitation in the central Hengduan Mountains. As shown in Fig. 11b, the up-sliding current in the west of the Hengduan Mountains is reduced, and the subsiding flow over the dry region is also diminished. Meanwhile, the specific humidity downstream of the removed mountains increases significantly (Fig. 11c). These results support the mechanism proposed in the previous section: the western mountains force an unfavorable circulation pattern for precipitation over the dry region and block the transportation of water vapor.

The rainfall anomalies associated with the highland to the east of the dry region are presented in Fig. 12a. After the topography higher than 2000 m is cut off (Fig. 9c), the rainfall on the eastern side of the Hengduan Mountains decreases significantly. In contrast, the precipitation amount in the dry region increases. The maximum rainfall change exceeds 3 mm/day in the northern dry region, which is far greater than the local climatic March precipitation amount. Figure 12b presents the shifts in specific humidity. More water vapor is transported to the central Hengduan Mountains and the specific humidity increases by more than 1.5 g/kg. The rainfall and specific humidity change patterns shown in Fig. 12 provide the evidence that the elevated terrain to the east of the dry region prevents the moist easterly flow from entering the central Hengduan Mountain region, and contributes to the formation of the severe dry spells.

Comparing the results of the two sensitivity experiments, it is found that the S1 experiment not only diminishes the subsiding flow over the dry region, but also leads to larger changes in specific humidity above the
surface. The S2 experiment mainly increases the specific humidity over the northern side of the dry region. It should be noted that in S1 the western mountains are still higher than the dry region, whereas in S2 the zonal topography gradient between the dry region and the eastern highlands is removed. Nevertheless, the analysis shows that the specific humidity averaged over the major dry region (24–28°N and 100–103°E) increases by 0.84 g/kg in S1, which is much larger than the rise in S2 (0.33 g/kg). Therefore, the western north-south-oriented ridges block much more water vapor than the eastern highlands. Although the change in rainfall is larger in the S2 experiment, the rainfall increase is concentrated along 101°E and is closely related to the excessive orographic uplift due to the strengthened low-level easterly wind. Therefore, the western mountains might play a more important role in the formation of the dry conditions in the central Hengduan Mountains.

The results of the numerical experiments confirm the impacts of the topography on the early-spring dry spell. Reducing the topographic height on either the western or eastern side of the dry region significantly enhances
the rainfall amount and raises the specific humidity. Therefore, topography effects do contribute to the early-spring dry spell in the central Hengduan Mountains.

6. Summary

The climatic characteristics of the early-spring dry spell in the southeastern margin of the Tibetan Plateau have been analyzed by comparing the climate over the major dry region and that on the western and eastern sides of this region, and the mechanisms related to topographic forcing have been investigated. The major conclusions are summarized below:

1. Over the central Hengduan Mountains, relative humidity reaches its annual minimum and the evaporation is at its strongest in early spring; further, the rainfall amount is extremely low. This situation is in stark contrast to that in the surrounding regions, which have high relative humidity and rainfall amounts.

2. In the major dry region, more than 80% of the days in March and April are “dry” days. The mean duration of the early-spring dry spell exceeds one week. The total number of early-spring dry spell events that last for 10 days or longer was more than 50 for the period 1961–2004.

3. The early-spring dry spell over the central Hengduan Mountains is partly attributed to the influence of the topographical conditions on the local atmospheric circulation. The mountains lying to the west of the dry region force the westerly flow to rise, causing heavy rainfall over the windward side and blockage of water vapor transportation. The sinking flow over the dry region suppresses precipitation and contributes to an increase in the surface air temperature. The mountains lying to the east of the dry region obstruct the moist easterly wind and help maintain the cloudy, rainy weather east of the Kunming Quasi-Stationary Front; this also contributes to the dry spell.

4. Because of its adequate horizontal resolution, the CREM can be used to capture the major characteristics of the early-spring rainfall pattern. The sensitivity experiments performed using the CREM reveal that the weakened topographic forcing on the western or eastern side of the dry region can lead to a significant increase in the early-spring rainfall in the central Hengduan Mountains. These results confirm the role of topographic forcing in the formation of the early-spring dry spell.

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