Chin. Geogra. Sci. 2018 Vol. 28 No. 4 pp. 680–693
https://doi.org/10.1007/s11769-018-0973-3

Springer Science Press
www.springerlink.com/content/1002-0063

Daily SPEI Reveals Long-term Change in Drought Characteristics in Southwest China

JIA Yanqing[1,2], ZHANG Bo[1], MA Bin[1]

(1. *College of Geography and Environmental Science*, *Northwest Normal University*, *Lanzhou* 730070, *China*; 2. *Department of Geography*, *Xinzhou Normal University*, *Xinzhou* 034000, *China*)

Abstract: Drought is the most widespread and insidious natural hazard, presenting serious challenges to ecosystems and human society. The daily Standardized Precipitation Evapotranspiration Index (SPEI) has been developed to identify the regional spatiotemporal characteristics of drought conditions from 1960 to 2016, revealing the variability in drought characteristics across Southwest China. Daily data from142 meteorological stations across the region were used to calculate the daily SPEI at the annual and seasonal time scale. The Mann-Kendall test and the trend statistics were then applied to quantify the significance of drought trends, with the following results. 1) The regionally averaged intensity and duration of all-drought and severe drought showed increasing trends, while the intensity and duration of extreme drought exhibited decreasing trends. 2) Mixed (increasing/decreasing) trends were detected, in terms of intensity and duration, in the three types of drought events. In general, no evidence of significant trends ($P < 0.05$) was detected in the drought intensity and duration over the last 55 years at the annual timescale. Seasonally, spring was characterized by a severe drought trend for all drought and severe drought conditions, while extreme drought events in spring and summer were very severe. All drought intensities and durations showed an increasing trend across most regions, except in the northwestern parts of Sichuan Province. However, the areal extent of regions suffering increasing trends in severe and extreme drought became relatively smaller. 3) We identified the following drought hotspots: Guangxi Zhuang Autonomous Region from the 1960s to the 1990s, respectively. Guangxi Zhuang Autonomous Region and Guizhou Province in the 1970s and 1980s, and Yunnan Province in the 2000s. Finally, this paper can benefit operational drought characterization with a day-to-day drought monitoring index, enabling a more risk-based drought management strategy in the context of global warming.

Keywords: drought; spatial-temporal characteristics; variability; daily Standardized Precipitation Evapotranspiration Index (SPEI); Southwest China

Citation: JIA Yanqing, ZHANG Bo, MA Bin, 2018. Daily SPEI Reveals Long-term Change in Drought Characteristics in Southwest China. *Chinese Geographical Science*, 28(4): 680–693. https://doi.10.1007/s11769-018-0973-3

1 Introduction

Drought is a recurring natural phenomenon that occurs in virtually all climate zones, and has presented a problem throughout human history (Campos, 2015; Hao and Singh, 2015; Thomas and Prasannakumar, 2016). Drought has widely varying impacts, on sectors such as agriculture, the economy and ecosystems, with diverse spatial and temporal distributions (Andreadis and Lettenmaier, 2005; Singh et al., 2014; Song et al., 2015; Awange et al., 2016; Modarres et al., 2016; Zhu et al., 2016). It is among the costliest of natural disasters, causing an annual agricultural economic loss of 27.2 billion yuan (RMB) in China (Song et al., 2014). The

Received date: 2017-12-11; accepted date: 2018-04-05
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41561024), Philosophy Social Science Foundation of Shanxi Province of China (No. 2015265)
Corresponding author: ZHANG Bo. E-mail: zhangbo@nwnu.edu.cn

devastating impacts of severe drought are well documented in China (Shen et al., 2012; Chen et al., 2016). As reported by Shen et al. (2012), the 2010–2011 severe drought in Shandong Province affected 3.2 million people, impacted 1.2×10^7 ha of winter wheat and reduced flow to zero in 366 rivers. Hebei Province experienced drought in 2010–2011 covering an area of approximately 714 580 ha, with 3.7 million people lacking adequate drinking water. The 2009–2010 drought in Southwest China affect 24.0 million people, costing the government about 4.1 billion RMB in drought relief programs that included relief supplies, contingency plans, and supply of portable water to the stricken areas (Huang et al., 2012). Economic losses caused by drought accounted for 19.4% of the total loss in 1985–2016 over China (Chen et al., 2016). Therefore, understanding the spatial and temporal variability of drought has a vital role in effective and sustainable drought mitigation and water resources management.

For studying and characterizing drought, several drought indices have been established, such as the Palmer Drought Severity Index (PDSI) (Palmer, 1965), Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982), Standardized Precipitation Index (SPI) (McKee et al., 1993) and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). The SPEI, the SPI and the PDSI are the most widely used drought indices to quantify characteristics of drought, each with its own strengths and weaknesses. The SPI is a normalized drought index which tracks meteorological drought (McKee et al., 1993; Hayes et al., 2011), so its value is unaffected by the local climatic and geographical conditions (Maity et al., 2016). Hence, the severity and duration of drought occurring at different places with different climatic conditions can be compared using SPI (McKee et al., 1993). However, SPI is based only on a precipitation probabilistic approach, which neglects the importance of the effect of warming on drought conditions. Although the PDSI includes the roles of precipitation, temperature and soil moisture percentile variables, it lacks the multi-scale characteristics that are essential to both characterizing drought conditions and evaluating different types of drought. Compared with the above two indices, the Standardized Precipitation Evapotranspiration Index (SPEI) proposed by Vicente-Serrano et al. (2010) assimilates the various drought-related variables, including precipitation and temperature, and combines the advantage of multiple meteorology variables with a simple calculation and flexible time scale. However, the monthly SPEI can only detect and monitor the frequency and severity of drought over the drought duration period and cannot be used for short scales (from daily to weekly). Sustained drought during a crop's key growth period is detrimental to its growth and development, resulting in weak growth and possible crop death. The monthly SPEI may be insufficient to fully characterize complicated drought conditions and their details, such as when the drought started and ended over a region, and how long it lasted (Lu et al., 2014). In this study, we will attempt to apply daily Standardized Precipitation Evapotranspiration Index to describe the physical characteristics of droughts including frequency, duration, severity, and spatial extent. The daily SPEI overcomes the deficiencies of the monthly SPEI; and it can monitor drought at scales from daily to weekly, monthly, and longer. Consequently, it is necessary to develop the daily drought index for drought monitoring and warning at different timescales.

Southwest China is one of the most important grain production regions. Drought has occurred at least once every year, with severe drought occurring every 5–10 years. The long and widespread droughts have led to a deficit of available water over the region (Huang et al., 2012). Rising temperature under global warming may increase the probability of drought, establishing drought more quickly and with greater intensity (Trenberth et al., 2013). Since 2000, drought hazards have occurred frequently in this region, with large agricultural and industrial losses (Zuo et al., 2014). Recently, water resources have been under increasing pressure from rapidly increasing demand associated with a growing population and economic development, such that the probability of drought in this region has sharply increased (Sharma et al., 2000). Although regions most at risk are predominantly restricted to arid and semi-arid areas (Mishra and Desai, 2005; Bhuiyan et al., 2006; Pandey et al., 2008; Thomas et al., 2015a; 2015b), the occurrence of drought in Southwest China, one of China's higher precipitation areas (600–2300 mm) reflects a decrease in precipitation and a more uneven precipitation distribution in the past several decades, increasing the region's vulnerability to drought. Previous studies have indicated that the region suffers from issues related to water resource management, agricultural production, and the regional economy

(Wang et al., 2010; Han et al., 2014; Song et al., 2014; Wang Q F et al., 2014). Hence, agricultural security and ecological restoration call for a detailed understanding of the spatiotemporal characteristics of drought. Although several studies have addressed drought characteristics at various spatial and temporal scales in Southwest China (Han et al., 2014; Li et al., 2014; Wang Dong et al., 2014; Yang et al., 2014), their conclusions have been limited by the temporal scale of drought conditions, with few studies explicitly presenting the attributes of drought characteristics required for agricultural risk assessment. The majority of previous studies focus exclusively on annual and seasonal time scales of drought over Southwest China, in the different spatial domains, using various methodologies (He et al., 2011; Su et al., 2014; Liu et al., 2015; Yang et al., 2015). Decision makers need to know the detailed characteristics of drought scenarios, including start and end time, the frequency of the various degrees of drought, and the duration and intensity of drought, rather than just knowing an averaged drought condition over a period of time. Therefore, we have applied the daily SPEI to monitor and detect day-to-day variations in drought across Southwest China.

To better understand the drought characteristics, the spatiotemporal variation of drought conditions, as well as the distribution of drought hotspots, were examined using daily meteorological data and drought analysis methods. The study aims to: 1) characterize the annual and seasonal temporal variability of drought at 142 stations in Southwest China; 2) assess the spatial variation of drought characteristics using the Mann-Kendall test; 3) and identify the inter-decadal distribution of drought hotspots.

2 Materials and Methods

2.1 Study area

The Southwest China region includes Yunnan Province, Guizhou Province, Sichuan Province, Guangxi Zhuang Autonomous Region and Chongqing Municipality, covering an area of approximately 1.37×10^6 km^2 and supporting a population of 257 million (Fig.1). The region extends between 20°N and 35°N and 98°E and 110°E. Southwest China is characterized by a very complex topography and exhibits large variations in elevation, ranging from –100 to 6512 m. The region's western, northwestern and central-eastern parts are mountainous or hilly, and account for over two thirds of the region's total area. The remaining areas are mostly plain and plateau. The region lies in the climatic transitional zone of the Tibetan plateau (towards the east and across the southern plain) and generally has a warm, sunny climate influenced by the monsoon and mountainous topography. Under these influences, its precipitation displays an uneven annual and decadal distribution. The annual mean temperature ranges from 14℃ to 24℃, and the average annual precipitation is in the range 600–2 300 mm with the summer and autumn (from May to October) bringing about 80%–90% of the annual mean precipitation over the area (Hu et al., 2015). There are marked seasonal variations in the region's precipitation distribution. The annual precipitation decreases from southeast to northwest, varying from over 2500 mm along the north coast of the Beibu Gulf (Guangxi Zhuang Autonomous Region) to less than 700 mm in the northwest and northeast of Yunnan Province (Liu et al., 2014).

2.2 Data

Daily meteorological data from 1960 to 2014 are collected at 142 synoptic stations administered by the China Meteorological Information Center (http://data.

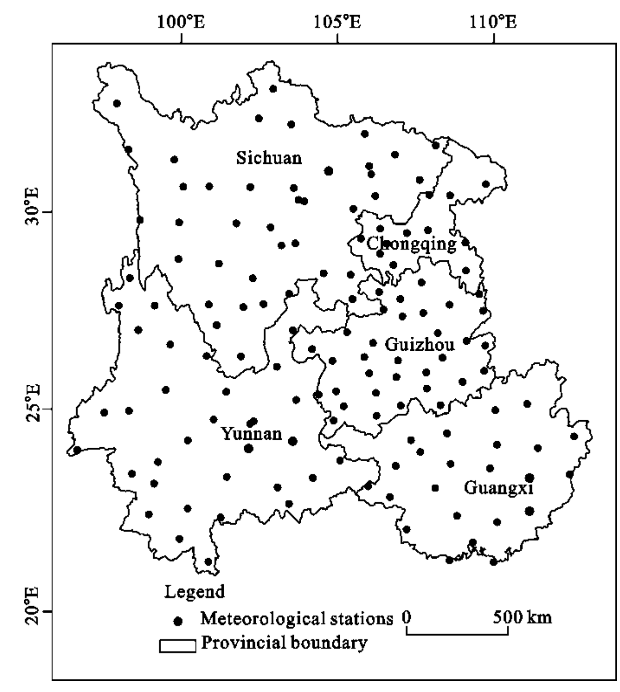

Fig. 1 Geographical position and regional distribution of the 142 meteorological stations in Southwest China

cma.cn), and include precipitation (mm), the minimum and maximum air temperature (℃), sunshine duration (h), wind speed (m/s) and relative humidity (%) (Fig.1). The limited meteorological data of the climatic records such as sunshine and wind speed at stations were checked and completed using multi-year averaging values. Potential evapotranspiration (ET_0) was calculated by using Penman-Monteith method (Penman, 1948). The simulated values are automatically substituted for the missing values in the calculation formula, and have little effect on the final result (Liu and Pereira, 2001).

2.3 Method

2.3.1 Calculation of daily SPEI

The SPEI is a widely used drought index based on ahydro-climatic water balance, which is the difference between precipitation and ET_0, calculated by standardizing the difference between ET_0 and precipitation. The monthly SPEI has been developed and transformed into a daily SPEI index in this study, this index used to analyze the trend of drought. The daily SPEI can simultaneously describe drought characteristics at short time scale (day, week, ten days, month) and long time scale (year), expresses more precisely the degrees of drought/flood in the study period. The calculation of the daily SPEI is very similar to that of the monthly SPEI used to identify and monitor different drought types. It is briefly described by Vicente-Serrano et al. (2010) and Wang et al. (2015).

2.3.2 Trend analysis method

To assess temporal trends in drought characteristics, we performed a linear trend analysis to detect trends in three types of drought events in Southwest China. To assess spatial patterns in drought characteristics, we applied the M-K trend test to investigate the trend variability of drought intensity and duration (Tabari et al., 2012). Drought hot spots were identified by computing the annual average values of drought frequency and duration each decade.

2.3.3 Drought variables: frequency, intensity and duration

The 30-day (1-month) time scale for SPEI was adopted as a good indicator of changes in drought (Li et al., 2012), and daily precipitation and ET_0 data from 1960 to 2016 at 142 meteorological stations in Southwest China were used to compute the daily SPEI for 30-day time scale.

From the daily SPEI time series, annual total drought frequency, annual total drought intensity, and annual total drought duration for each station were also computed. We used the model proposed by Yevjevich (1969) and Spinoni et al. (2015) to define the drought related variables. The definitions of McKee et al. (1993) for the SPI were adapted, once a drought event was identified by its start and end day (Wang et al., 2015). In addition, the drought events were classified into three different categories: all drought, severe drought and extreme drought, according to values of the daily SPEI and the drought duration. We assumed that an all-drought event began whenever the SPEI value remained below a specified threshold (≤–0.5) for at least 15 consecutive days, and ended after exceeding a second specified threshold (>–0.5). A drought event was deemed severe if the daily SPEI values were less than –0.5 and persisted for more than 30 days but less than 45 days, and was deemed extreme if the daily SPEI values were less than –0.5 and persisted for more than 45 days. The annual total drought frequency represents the total number of drought events during the year. Annual total drought intensity represents the sum, in absolute values, of all the daily SPEI values of the drought events at each station. Annual total drought duration was calculated as the number of days classified as drought during the year.

3 Results and analyses

3.1 Inter-annual variability of drought characteristics

The variations in annual drought intensity and duration of three types of drought were calculated using daily SPE in the entire region and individually in the five sub-regions (Fig. 2). Drought intensity and duration of the corresponding drought types showed very similar temporal behaviors in the entire region and five sub-regions. Multi-year fluctuations were evident with different temporal patterns and trends over the period of 1960–2016.

Analysis of variations in annual intensity and duration of all-drought events over Southwest China in 1960–2016 (Figs.2a, 2a1–2a5) shows the following major characteristics: 1) meteorological drought trend analysis has shown a positive trend in both drought duration and intensity across the entire region, Guangxi Zhuang Autonomous Region, Guizhou, Yunnan Province, Chongqing and a negative trend in Sichuan Province. 2) Between 1960 and 2016, the average annual drought intensity and duration of drought events in Southwest China were 119 and 104 d, respectively. 3) There were substantial variations in intensity and duration across the five sub-regions of Southwest China. Average annual drought intensity was greatest (128) in Yunnan Province and lowest in Chongqing (111). Similarly, the longest drought duration was found in Yunnan Province (116 d) and lowest value in Chongqing (89 d).

Analysis of the variations of annual intensity and duration of severe drought in Southwest China during 1960–2016 (Figs. 2b, 2b1–2b5) reveal the following trends. 1) The trends in severe drought intensity and duration differ, with an increasing trend in the entire region, Guangxi Zhuang Autonomous Region, Guizhou, Yunnan Province and Chongqing, and decreasing trends in Sichuan Province. 2) The average annual severe

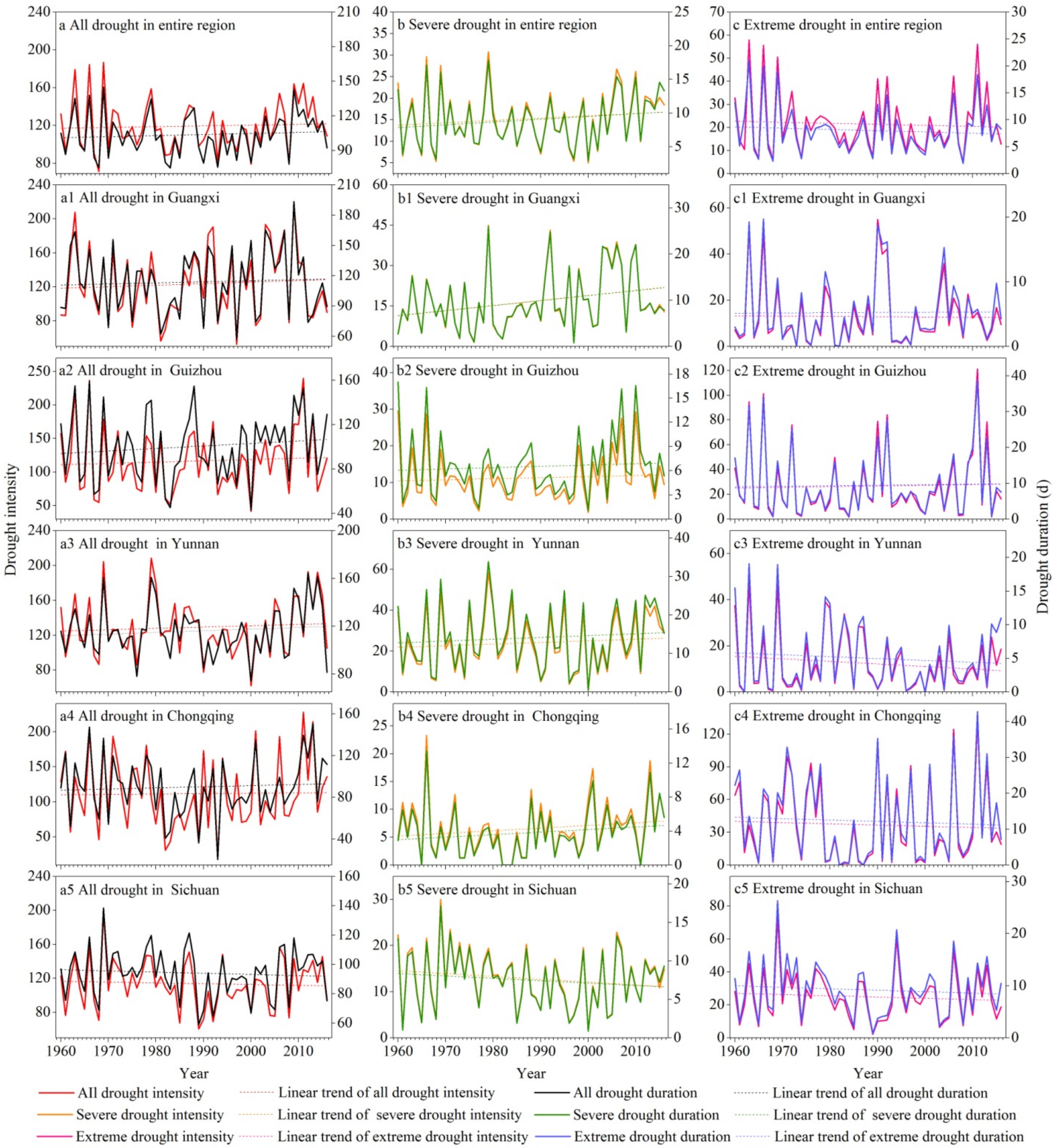

Fig. 2 Inter-annual variation in drought characteristics across Southwest China during 1960–2016

drought intensity and duration in Southwest China were 15 and 8 d, respectively. The largest and smallest severe drought durations and intensity occurred in 1979 and 2000, respectively. 3) Among the different sub-regions, severe drought intensity was highest in Yunnan (24) and lowest in Chongqing (6). Severe drought duration displayed similar temporal behavior, with highest values in Yunnan (14 d) and lowest values in Chongqing (4 d).

Analysis of the trends in annual extreme drought intensity and duration in Southwest China from 1960 to 2016 (Figs.2c, 2c1–2c5) show the following major characteristics: 1) Both drought intensity and duration showed a decreasing trend in the entire region, Guangxi Zhuang Autonomous Region, Yunnan, Sichuan Province and Chongqing, and an increasing trend in Guizhou Province. 2) The average annual extreme drought intensity and duration over the entire region were 22 and 8 d, respectively. 3) Average annual intensity of extreme drought was highest in Chongqing (37) and lowest in Yunnan Province (12). The extreme drought duration, on average, exhibited highest value across Chongqing (12 d) and lowest value in Yunnan Province (4 d).

Agriculture production has been severely affected by the drought disasters. Some studies showed that the 2011–2012 severe drought in Southwest China have affected agriculture production, 1.4×10^6 ha had been severely damaged. Mean annual area covered by drought, the area affected by drought and the area of crop failures all showed an increasing trend, which were 2.12×10^6, 9.4×10^5, 1.6×10^5 ha, respectively (Li et al., 2010).

3.2 Seasonal variations of drought characteristics

Fig. 3 shows seasonal variations in intensity and duration of all drought, severe drought, and extreme drought in Southwest China from 1960 to 2016. It is clear that fluctuations in total intensity and duration of all drought and severe drought events were more pronounced in spring than in other seasons (Figs.3a, 3b). The minimum medians for intensity and duration of all drought and severe drought occurred in the summer, while the maximum medians occurred in the spring. A clear decreasing trend in medians of the intensity and duration of all drought and severe drought can be seen from spring to summer, but from summer to autumn to winter, the trend was increasing. Different seasonal tendencies can be seen in Fig.3c which shows the extreme drought intensity and duration in the four seasons. The extreme drought intensity and duration both presented a rising trend from spring to summer and decreasing trend from summer to autumn to winter. The maximum medians of intensity and duration occurred in summer, and minimum medians in winter. The medians of duration in spring were close to those in summer, and extreme drought intensity and duration have shown similar trends in autumn and winter over the last 55 years. Overall, the values of intensity and duration for all drought and severe drought were more concentrated in summer, autumn and winter and more variable in spring; the values of intensity and duration for extreme drought were more concentrated in autumn and winter and more variable in spring and summer.

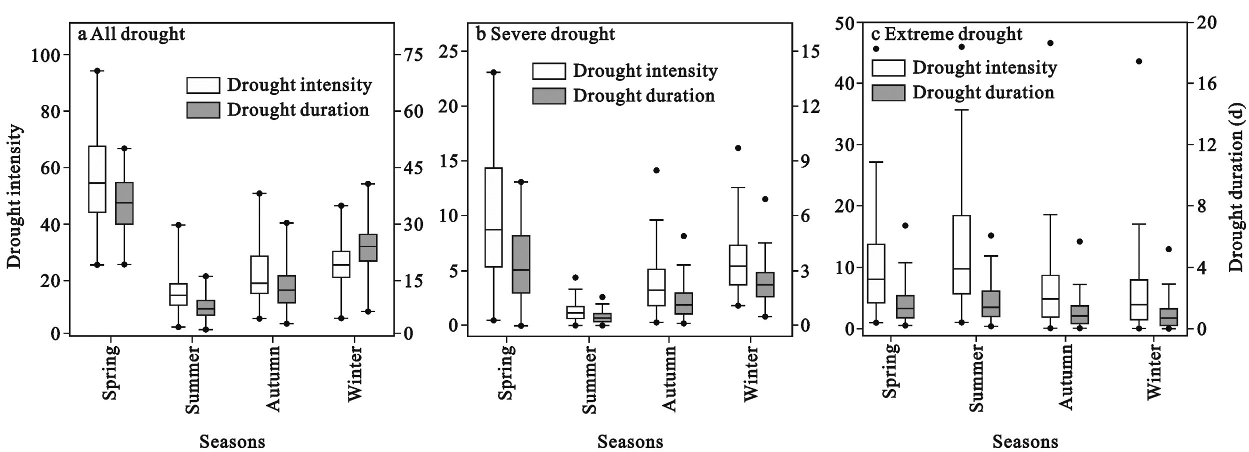

Fig. 3 Seasonal variations of three types of drought intensity and duration in Southwest China from 1960 to 2016

3.3 Regional trend in drought characteristics

Of the 142 meteorological stations studied, the five regions of the study area (Sichuan, Chongqing, Yunnan, Guizhou and Guangxi Zhuang Autonomous Region) contained 38, 12, 32, 35, and 25 stations, respectively. The regional trend assessment was conducted by applying the trend statistics (z-value and trend magnitude (k value)) to the drought characteristics time series, which were average values from each station over the period 1960–2016. The spatial distribution of the temporal trend statistic z values of intensity and duration for the three types of drought events were interpolated across the entire study region in Fig. 4.

3.3.1 Trend of drought intensity

An analysis of the annual all drought intensity time-series using the M-K test found that more stations had positive trends (92 of 142 stations, 65%) than negative trends (Fig. 4a). However, only 19 were found to have significant positive trend while 12 had significant negative trends ($P < 0.5$). Regions with the strongest increasing trends of drought intensity were found in the southwestern and central part of the study region. Significant negative trends were mostly found in the western part of the region. The magnitude of the trend varied between –5.5 and 4.0 per year. The severe drought intensity series demonstrated an increasing trend over the study area for the majority of stations (88 of 142: 62%) and decreasing trend in (Fig. 4b) the remain stations. A total of 27 stations (18 positive and 9 negative) were found to have significant trend ($P < 0.5$), of which the 18 stations with positive trends were mostly found in southern Sichuan, southwestern Yunnan, and southeast Guangxi Zhuang Autonomous Region, while the 9 stations with negative trends were located in northwestern Sichuan and northern Guizhou Province. The regional averages of positive and negative trends were 4.1 and –3.5 per year ($P < 0.5$), respectively.

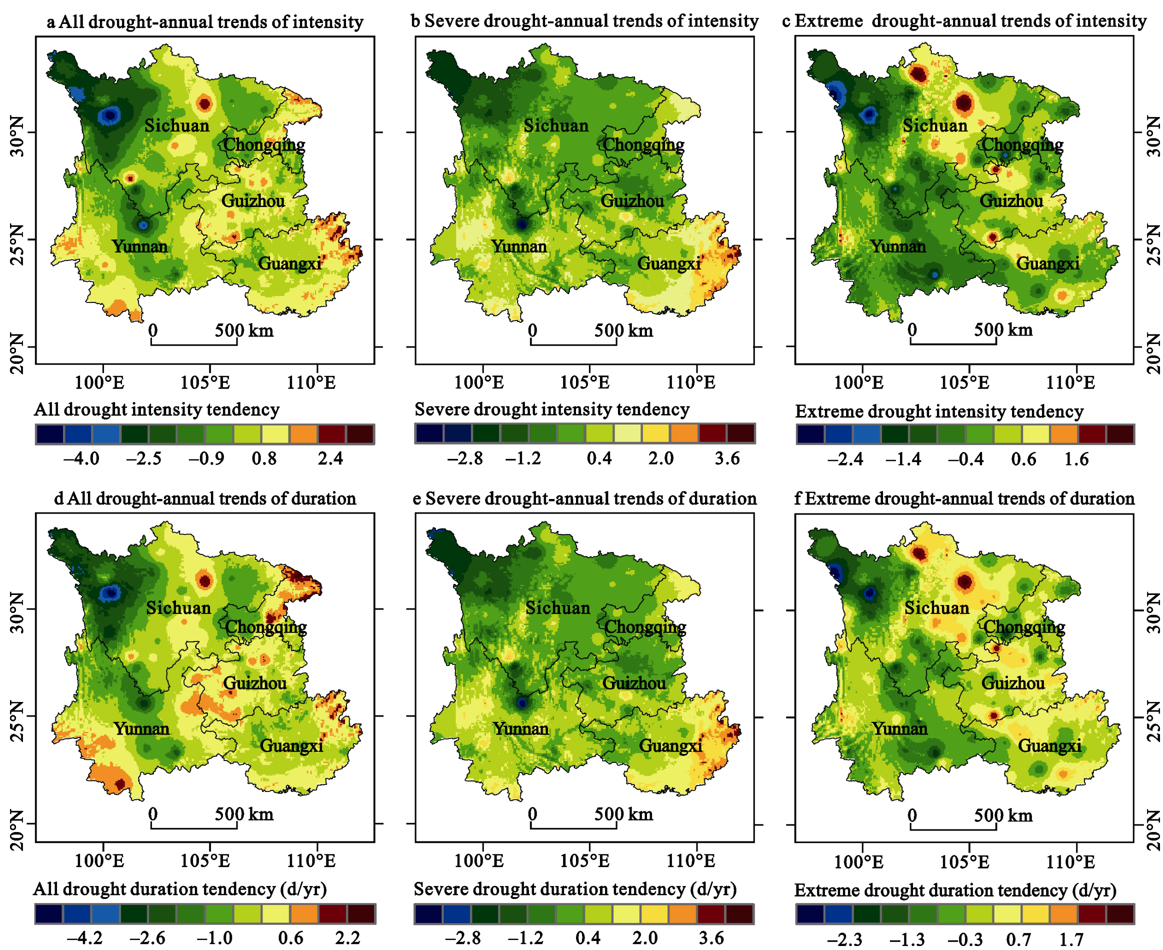

Fig. 4 Spatial trends of drought intensity and duration of all-drought, severe drought and extreme drought in Southwest China from 1960 to 2016

Extreme drought intensity displayed a weakly decreasing trend when compared with that of all- and severe drought intensity (Fig. 4c). In this case, 76 (54%) stations and 66 (46%) stations showed negative and positive trends, respectively. Over half of areas showed weak negative trends, except for some eastern parts of the study area. 16 stations with significant negative trends were scattered across Sichuan and Yunnan Provinces. Extreme drought intensity trend varied between –1.1 and 2.2 per year ($P < 0.5$).

3.3.2 Trend of drought duration

As shown in Fig. 4d, 65% of the stations experienced increasing trends in all drought duration, of which 19 were significant ($P < 0.5$). The other 35% of stations showed negative trends. Stations with significant positive trends were mostly found in southeastern Sichuan, southwestern Yunnan and northern and western Guizhou Province. The areas with significant decreasing trend were distributed in western Sichuan and eastern Yunnan Province. The magnitudes of trend varied between –5.0 and 4.6 d/yr.

The regional distribution of severe drought duration assessed using the M-K test found positive trends at 63% of stations and negative trends at the remainder (Fig. 4e). Two areas in the west and southeast of the region showed significant increasing trends, only 9 stations with significant decreasing trends. Fig. 4e also shows that trends varied between –4.3 d and 5.2 d/yr.

As Fig. 4f shows, extreme drought duration assessed using the M-K test found increasing trends in about half of the stations and decreasing trends in the remaining stations. A total of 27 stations (9 positive and 18 negative) experienced statistically significant varied trends ($P < 0.5$). Stations with significant positive trends were scattered across the western region, while those with significant negative trends were mainly located in some eastern parts of the study region. Corresponding trend magnitudes varied between –1.8 d and 1.6 d/yr. The intensity and duration of extreme drought demonstrated decreasing trends moving from east to west across the region.

3.4 Meteorological drought hotspots in Southwest China during 1960–2016

In order to detect drought hotspots during the last 57 years in Southwest China, we computed the annual average frequency and duration of all drought events during the five sub-periods and during the entire period (Figs. 5, 6), i.e., 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, and 1960–2016. The drought frequency, duration and dominant areas showed marked inter-decadal variations. In the period 1960–1969, drought frequency (Fig. 5a) showed high values in Guangxi, Guizhou, Chongqing, and parts of western Sichuan. Drought duration (Fig. 6a) displayed high values in Yunnan, Guangxi and southern Sichuan. Frequent and sustained drought events occurred in Guangxi. In the period 1970–1989, the distribution of drought frequencies in 1970s (Fig. 5b) was similar to that in the 1980s (Fig. 5c). During above two decades, high values of maximum frequency, which could be regarded as outliers, occurred in Guizhou and Guangxi Zhuang Autonomous Region, reaching 27 times, while elsewhere the frequency ranged from 8 times to 26 times. Generally, drought frequency tended to decrease from southeast to northwest in 1970s and 1980s. In the period 1970–1979, the areas with higher drought duration (Fig. 6b) were located mainly in northern Sichuan, Guangxi, and middle-northern Guizhou. As shown in Fig. 6c, the region suffering from drought during 1980–1989 expanded to cover almost the entire western and southeastern parts the region. In the period 1990–1999 (Fig. 6d), the areas suffering prolonged drought receded to the southern parts of Southeast China. At the same time, drought events occurred more frequently in Guangxi, Guizhou and Chongqing (Fig. 5d). In the period 2000–2009 (Fig. 6e), drought duration was generally greatest in the south of the region, frequent droughts also occurred in the west of the region (Fig. 5e). In the period of 1960–2016, areas with higher drought frequency (Fig. 5f) were mainly located in the southeastern parts of the region, where the average drought frequencies ranged from 160 times to 182 times. Either frequent or long drought events occurred in southern Southwest China, where the average annual drought duration ranged from 67 to 133 d (Fig. 6f).

According to previous research, the most relevant drought events affecting the drought hotspots are those in the 1960s and 2000s. In particular we note the drought in western Southwest China in the 2000s (Su et al., 2014), the widespread autumn and winter drought of 2009–2010 in Yunnan Province (Yang et al., 2012), and frequent drought events in the west Sichuan Plateau in 1958–2012 (Yao et al., 2015). Comparing our results

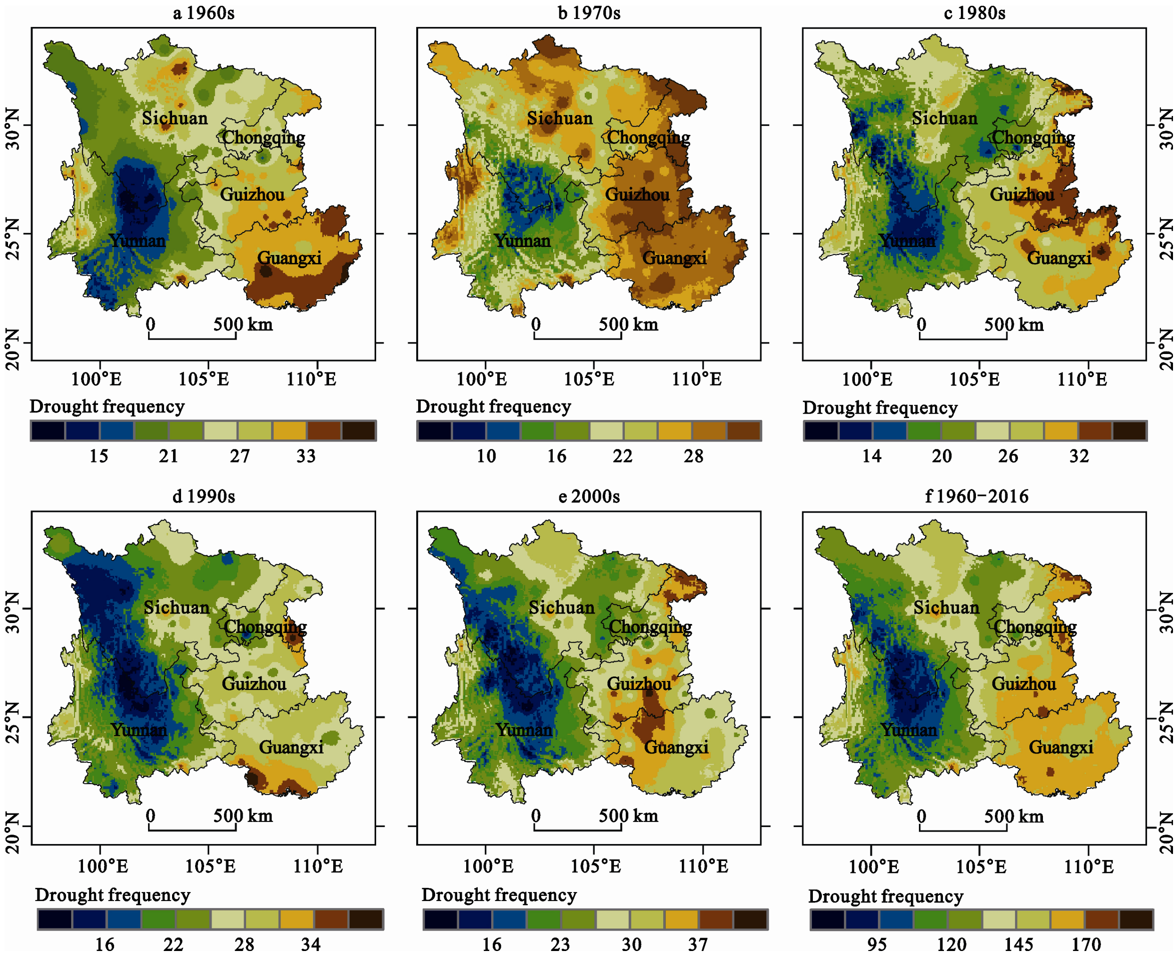

Fig. 5 Drought frequency during individual decades and for the full period 1960–2016 in Southwest China

with those presented in Su et al. (2014) and Wang Dong et al. (2014) based on a different dataset, we notice no difference regarding locations of the hotspots in the different decades of the 57-year study period.

Statistics show that the comprehensive loss rate of crops caused by drought increased gradually in recent 60 years in Southwest China. The loss rate of crop caused by drought in 21st century is 7.3%, which is higher than the national average level (5.5%) (Han et al., 2014). Especially in mid-September 2009 to March 2010, Southwest China suffered from serious extreme drought disasters, the winter wheat, rape and sugarcane production are reduced by severe drought disaster in northwestern Guangxi Zhuang Autonomous Region, Southwestern Guizhou Province, central part and northeast Yunnan Province. The yield loss of winter wheat reached 8.3×10^5 t, accounting for 13.7% of the total yield of winter wheat over Southwest China in 2009. The winter wheat production dropped by 31% and 48% in Guizhou and Yunnan Province, respectively (Li et al., 2010).

4 Discussion

Drought can be characterized by several indices (Mishra and Singh, 2010; Zargar et al., 2011). In recent years, the number of studies on the quantification of drought frequency, duration and intensity in China has been growing rapidly, with varying areal extents and different indices being considered (Huang et al., 2010; Xiong et al., 2013; Zhang et al., 2016). Because of the complexity of drought conditions and their wide impacts, it is important to modify drought analyses based on qualitative information (Steinemann, 2003).

On the basis of the daily Standardized Precipitation Evaporation Index, this study analyzed the behavior and trends of drought characteristics between 1960 and 2016

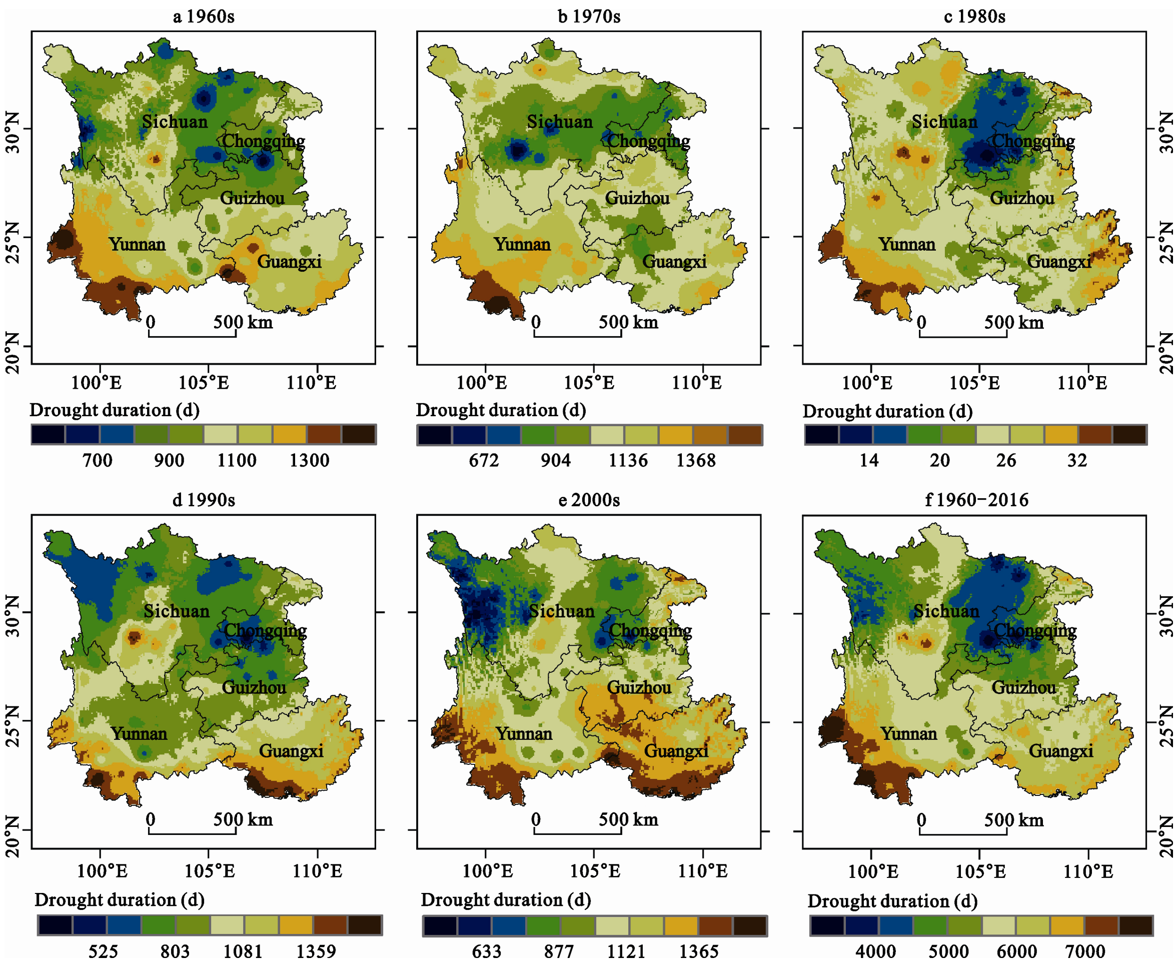

Fig. 6 Drought duration during individual decades and for the full period 1960–2016

in Southwest China. Dealing with meteorological and agricultural drought, the most important sources of uncertainties, such as climate forcing factors, local patterns, feedbacks, baseline period, input data reliability (precipitation in particular), natural climate variability *etc.* are listed by Trenberth et al. (2013). Fundamentally, drought relates to the amount of water available in soils or hydrological systems. It obviously depends greatly on precipitation and ET_0, but it also depends on how much water infiltrates to deeper ground or runs off the land and how much is evaporated or transpired by plants. Furthermore, the air temperature influences the moisture content in the atmosphere, which strongly influences ET_0. The latter also relies on surface humidity and wind, which dictate what proportion of the moisture is carried away (Trenberth et al., 2013). Thus, the choice of methodology for computing ET_0 is crucial to understand and detect drought characteristics. The original SPEI uses the 'Thornthwaite method' (Dai, 2011; Schrier et al., 2011; Sheffield et al., 2012) to account for the ET_0 effect. This approach may depend too much on temperature, without considering other factors (relative humidity, wind speed, and solar radiation) that are included in ET_0 computed with the Penman-Monteith's approach (ET_{0PM}) (Allen et al., 1998). Based on this, we opted for the Penman-Monteith model to calculate ET_0. This is in view of taking the baseline as the entire period (1960–2016) in the spatiotemporal analysis of drought characteristics to minimize biases based on short periods. To address uncertainties in the input we quality-checked the input datasets and improved their homogeneity to ensure the highest possible data quality.

In the past several decades, numerous studies have committed to determine the onset, end point and severity of drought as a means of drought quantification, effective monitoring and establishment of early warning systems (Dai, 2011; Thomas et al., 2015a; Liu et al., 2016; Zhang et al., 2016). Previous work has revealed that Southwest China has experienced a warming-drying climatic tendency with increasing temperature and declining precipitation (Wang et al., 2012; Han et al., 2014; Su et al., 2014; Wang Dong et al., 2014; Liu et al., 2015). Consequently, the drought severity and frequency have increased across Southwest China in recent years, as quantified by various drought indices (Xiong et al., 2013; Xu et al., 2013; Liu et al., 2014). Our study also found that annual characteristics of all-drought and severe drought conditions displayed similar temporal behavior, i.e., the annual intensity and duration of all- and severe drought displayed increasing trends during 1960–2016. Our results, based on daily SPEI index, generally agree with other recent studies (Han et al., 2014; Su et al., 2014; Wang Dong et al., 2014). However, our results found that extreme droughts in Southwest China have followed decreasing trends over the past 57 years. In contrast to our findings, Liu et al. (2015) found that extreme drought became more serious in Southwest China from 1960 to 2009. This contradiction may be attributed to our choice of daily SPEI and the influence of certain factors on drought conditions. Previous studies have shown that the trends in drought severity based on the SPEI time series were much smaller than those based on the SPI time series. Moreover, the apparent upward trend in drought severity was revised to a downward trend in some places after considering the effects of the elevated temperature on drought conditions (Liu et al., 2016). One possible explanation of this discrepancy could be that trends in ET_0 and precipitation were not synchronous in time. This would alter the probability distribution of the water time series and may lead to a weaker declining trend in the daily SPEI time series. Furthermore, as a result of the complexity of the link between evapotranspiration and drought severity, the effect of evapotranspiration on available water resources at various time scales has remained poorly understood.

We identified hotspots of drought frequency and duration during individual decades in Southwest China. The most marked increase in drought duration occurred in southwestern Yunnan Province and southeastern Guangxi Zhuang Autonomous Region. The most marked decrease in drought duration occurred largely in northwestern Sichuan Province. The most notable increase in drought frequency occurred in the southeast of the region and southwest of the Sichuan basin, consistent with the spatial pattern of drought frequency (Yin and Li et al., 2013; Wang Dong et al., 2014). The above results may explain the discrepancies between our conclusions and other studies, and will facilitate a better understanding of the characteristics of recent drought events over Southwest China.

In the relatively dry-type abnormal years in the entire area, the East Asia major deep trough was relatively weaker or eastward than normal years, and the cold air was difficult to invade southward; an abnormal cyclonic circulation was maintained over the lower layer of the South China Sea, and the warm and wet airflow transport in southwest China was relatively weak; and the subtropical high over the Western Pacific was relatively strong and stretched westward, the area of the South Asian high was relatively large and overlapped with subtropical high over the Western Pacific, and the Southwest China was controlled by high pressure for a long time. The maintenance of such anomalous circulation pattern made the area sunny and rainless, with relatively high air temperature and persistent drought. The relatively wet-type abnormal years presented opposite circulation characteristics. Abnormal vertical motion over the east and the west of the Southwest China and south and north wind anomalies at the eastern lower layer were important reasons for the East wet (dry)-West dry (wet) type anomaly.

5 Conclusions

We use the daily SPEI to monitor the seasonal and annual drought across Southwest China. The process of drought changes is consistent with the developing process of historical drought. The animation of daily SPEI is used to display the day-to-day variation of the drought and examine the details of the drought process. It can show when the drought emerged over the Southwest China and when it relieved over the region. The daily SPEI is therefore an effective tool for drought monitoring, especially for the day-to-day monitoring, and possesses the capability to announce the onset, duration, and intensity of the drought over each specific area. The following conclusions can be drawn from this study:

(1) In general, the regionally-averaged intensity and duration of all- and severe drought all exhibited increases over the past 57 years, while the intensity and duration of extreme drought showed a decrease during

the same period. Seasonally, the inter-annual changes in intensity and duration of drought were consistent during the same season. High values of intensity and duration of the three types of drought demonstrated that there has been a trend towards severe drought in spring, and that extreme drought events in spring and summer have been particularly intense.

(2) The intensity and duration of all-drought events increased at 65% of the stations. Regions with the significant positive trends were found in northern Sichuan, southwestern Yunnan and eastern Guangxi, the worst-hit areas were located in southern and eastern Guangxi. Severe drought intensity and duration increased at 62% and 63% of stations, respectively. Two areas in southwestern Yunnan and southeastern Guangxi showed significant increasing trends. Almost equal numbers of stations showed positive and negative trends in annual intensity and duration of extreme drought events. Stations with significant negative trends were mainly located in some western parts of the study region, those areas with significant positive trends were scattered across the eastern region.

(3) Areas prone to prolonged drought were distributed in central and southern Southwest China. Areas prone to frequent droughts were mainly located in the southeastern region of the study area, but in different decades. However, the distribution of drought hotspots has changed during recent decades. The area suffering from frequent droughts was found to significantly expand to cover most parts of the region in the 2000s when compared with other decades.

References

Abramowitz M, Stegun I, Romain J E, 1965. *Handbook of Mathematical Functions*, *with Formulas*, *Graphs*, *and Mathematical Tables*. New York: Dover Publications, 1046.

Ahmad M I, Sinclair C D, Werritty A, 1988. Log-logistic flood frequency analysis. *Journal of Hydrology*, 98(3): 205–224. doi: 10.1016/0022-1694(88)90015-7

Allen R G, Pereira L S, Raes D et al., 1998. *Crop Evapotranspiration*: *Guidelines for Computing Crop Water Requirements*. FAO irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations.

Andreadis K M, Lettenmaier D P, 2005. Trends in 20th century drought over the continental United States. *Geophysical Research Letters*, 33(10): 10–1029. doi: 10.1029/2006gl025711

Awange J L, Mpelasoka F, Goncalves R M, 2016. When every drop counts: analysis of drought in Brazil for the 1901–2013 period. *Science of the Total Environment*, 566: 1472–1488. doi: 10.1016/j.scitotenv.2016.06.031

Bhuiyan C, Singh R P, Kogan F N, 2006. Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data. *International Journal of Applied Earth Observation and Geoinformation*, 8(4): 289–302. doi: 10.1016/j.jag.2006.03.002.

Campos J B, 2015. Paradigms and public policies on drought in Northeast Brazil: a historical perspective. *Environmental Management*, 55(5): 1052–1063. doi: 10.1007/s00267-015-0444-x

Chen Jing, Liu Hongbin, Wang Yanjun et al., 2016. Variation of drought characteristics and its agricultural exposure in North China plain. *China Journal of Agrometeorology*, 37(5): 587–599. (in Chinese)

Dai A G, 2011. Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *Journal of Geophysical Research Atmospheres*, 116(D12): 1248-1256. doi: 10.1029/2010JD015541

Han Lanying, Zhang Qiang, Yao Yubi et al., 2014. Characteristics and origins of drought disasters in Southwest China in nearly 60 years. *Acta Geographica Sinica*, 69(5): 632–639. (in Chinese)

Hao Z, Singh V P, 2015. Drought characterization from a multivariate perspective: a review. *Journal of Hydrology*, 527: 668–678. doi: 10.1016/j.jhydrol.2015.05.031

Hayes M, Svoboda M, Wall N et al., 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, 92(4): 485–488. doi: 10.1175/2010bams3103.1

He Jinyun, Zhang Mingjun, Wang Peng et al., 2011. Climate characteristics of the extreme drought events in Southwest China during recent 50 years. *Acta Geographica Sinica*, 66(9): 1179–1190. (in Chinese)

Hu Xueping, Xu Pingping, Ning Guicai et al., 2015. Causes of continuous drought in Southwest China from autumn of 2012 to spring of 2013. *Journal of Desert Research*, 35(3): 763–773. (in Chinese)

Huang Ronghui, Liu Yong, Wang Lin et al., 2012. Analyses of the causes of severe drought occurring in Southwest China from the fall of 2009 to the spring of 2010. *Chinese Journal Atmospheric Sciences*, 36(3): 443–457. (in Chinese)

Huang Wanhua, Yang Xiaoguang, Li Maosong et al., 2010. Evolution characteristics of seasonal drought in the south of China during the past 58 years based on standardized precipitation index. *Transactions of the Chinese Society of Agricultural Engineering*, 26(7): 50–59. (in Chinese)

Li Qiangzi, Yan Nana, Zhang Feifei et al., 2010. Drought monitoring and its impacts assessment in Southwest China using remote sensing in the spring of 2010. *Acta Geographica Sinica*, 65(7): 771–780. (in Chinese)

Li Weiguang, Yi Xue, Hou Meiting et al., 2012. Standardized Precipitation Evapotranspiration Index shows drought trends in China. *Chinese Journal of Eco-Agriculture*, 20(5): 643–649. (in Chinese)

Li Yunjie, Ren Fuming, Li Yiping et al., 2014. A study of the characteristics of the southwestern China regional meteorological drought events during 1960–2010. *Acta Meteorologica Sinica*, 72(2): 266–276. (in Chinese)

Liu B J, Chen C L, Lian Y Q et al., 2015. Long-term change of wet and dry climatic conditions in the southwest karst area of China. *Global and Planetary Change*, 127(4): 1–11. doi: 10.1016/j.gloplacha.2015.01.009

Liu M X, Xu X L, Sun A Y et al., 2014. Is southwestern China experiencing more frequent precipitation extremes? *Environmental Research Letters*, 9(3–4): 479–489. doi: 10.1088/1748-9326/9/6/064002

Liu Yu, Pereira L S, 2001. Calculation methods for reference evapotranspiration with limited weather data. *Journal of Hydraulic Engineering*, 2001(3): 11–17. (in Chinese)

Liu Z P, Wang Y Q, Shao M A et al., 2016. Spatiotemporal analysis of multiscalar drought characteristics across the Loess Plateau of China. *Journal of Hydrology*, 534(534): 281–299. doi: 10.1016/j.jhydrol.2016.01.003

Lu E, Cai W, Jiang Z et al., 2014. The day-to-day monitoring of the 2011 severe drought in China. *Climate Dynamics*, 43(1–2): 1–9. doi: 10.1007/s00382-013-1987-2

Maity R, Suman M, Verma N K et al., 2016. Drought prediction using a wavelet based approach to model the temporal consequences of different types of drought. *Journal of Hydrology*, 539: 417–428. doi: 10.1016/j.jhydrol.2016.05.042

McKee T B, Doesken N J, Kleist J, 1993. The relationship of drought frequency and duration to time scales. *Eighth Conference on Applied Climatology*. American Meteorological Society: Anaheim, CA, 174–184.

Mishra A K, Desai V R, 2005. Spatial and temporal drought analysis in the Kansabati river basin, India. *International Journal of River Basin Management*, 3(1): 31–41. doi: 10.1080/15715124.2005.9635243

Mishra A K, Singh V P, 2010. A review of drought concepts. *Journal of Hydrology*, 391(1–2): 202–216. doi: 10.1016/j.jhydrol.2010.07.012

Modarres R, Sarhadi A, Burn D H, 2016. Changes of extreme drought and flood events in Iran. *Global Planetary Change*, 144(9): 67–81. doi: 10.1016/j.gloplacha.2016.07.008

Palmer W C, 1965. *Meteorologic Drought*. U. S.: Weather Bureau.

Pandey R P, Mishra S K, Singh R et al., 2008. Streamflow drought severity analysis of Betwa river system (INDIA). *Water Resources Management*, 22(8): 1127–1141. doi: 10.1007/s11269-007-9216-6

Penman H L, 1948. Natural evaporation from open water, hare soil and grass. *Proceedings of the Royal Society of London*, 193(1032): 120–145. doi: 10.1098/rspa.1948.0037

Schrier G V D, Jones P D, Briffa K R, 2011. The sensitivity of the PDSI to the Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration. *Journal of Geophysical Research Atmospheres*, 116(D3): 613–632. doi: 10.1029/2010jd015001

Shafer B A, Dezman L E, 1982. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. *Proceedings of the 50th Annual Western Snow Conference*, 50: 164–175. Fort Collins, CO: Colorado State University.

Sharma K P, Moore B I, Vorosmarty C J, 2000. Anthropogenic, climatic, and hydrologic trends in the Kosi Basin, Himalaya. *Climatic Change*, 47(1): 141–165. doi: 10.1023/A:1005696808953

Sheffield J, Wood E F, Roderick M L, 2012. Little change in global drought over the past 60 years. *Nature*, 491(7424): 435–438. doi: 10.1038/nature11575

Shen Xiaolin, Zhu Congwen, Li Ming, 2012. Possible causes of persistent drought event in North China during the cold during the cold season of 2010. *Chinese Journal Atmospheric Sciences*, 36(6): 1123–1134. (in Chinese)

Singh V P, Guo H, Yu F X, 1993. Parameter estimation for 3-parameter log-logistic distribution (LLD3) by Pome. *Stochastic Hydrology & Hydraulics*, 7(3): 163–177. doi: 10.1007/BF01585596

Singh D, Tsiang M, Rajaratnam B et al., 2014. Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nature Climate Change*, 4(6): 456–461. doi: 10.1038/nclimate2208

Song X Y, Song S B, Sun W Y et al., 2015. Recent changes in extreme precipitation and drought over the Songhua River Basin, China, during 1960–2013. *Atmospheric Research*, 157: 137–152. doi: 10.1016/j.atmosres.2015.01.022

Song Yanling, Cai Wenyue, Liu Yanju et al., 2014. Drought changes in Southwest China and its impacts on rice yield of GuiZhou Province. *Journal of Applied Meteorological Science*, 25(5): 550–558. (in Chinese)

Spinoni J, Naumann G, Vogt J, 2015. European drought climatologies and trends based on a multi-indicator approach. *Global Planetary Change*, 127(6): 50–57. doi: 10.1016/j.gloplacha.2015.01.012

Steinemann A, 2003. Drought indicators and triggers: a stochastic approach to evaluation. *Journal of the American Water Resources Association*, 39(5): 1217–1233. doi: 10.1111/j.1752-1688.2003.tb03704.x

Su Xiucheng, Wang Lei, Li Qilin et al., 2014. Study of surface dry and wet conditions in Southwest China in recent 50 years. *Journal of Natural Resources*, 29(1): 104–116. (in Chinese)

Tabari H, Abghari H, Talaee P H, 2012. Temporal trends and spatial characteristics of drought and rainfall in arid and semiarid regions of Iran. *Hydrological Processes*, 26(22): 3351–3361. doi: 10.1002/hyp.8460

Thomas J, Prasannakumar V, 2016. Temporal analysis of rainfall (1871–2012) and drought characteristics over a tropical monsoon-dominated State (Kerala) of India. *Journal of Hydrology*, 534: 266–280. doi: 10.1016/j.jhydrol.2016.01.013

Thomas T, Jaiswal R K, Nayak P C et al., 2015a. Comprehensive evaluation of the changing drought characteristics in Bundelkhand region of Central India. *Meteorology and Atmospheric Physics*, 127(2): 163–182. doi: 10.1007/s00703-014-0361-1

Thomas T, Nayak P C, Ghosh N C, 2015b. Spatiotemporal analysis of drought characteristics in the bundelkhand region of Central India using the standardized precipitation index. *Journal of Hydrologic Engineering*, 20(11): 05015004. doi: 10.1061/(asce)he.1943-5584.0001189

Trenberth K E, Dai A, Schrier G V D et al., 2013. Global warming and changes in drought. *Nature Climate Change*, 4(1): 17–22. doi: 10.1038/nclimate2067

Vicente-Serrano S M, Beguería S, López-Moreno J I, 2010. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23(7): 1696–1718. doi: 10.1175/2009jcli2909.1

Wang Dong, Zhang Bo, An Meiling et al., 2014. Temporal and spatial distributions of drought in Southwest China over the past 53 years based on Standardized Precipitation Evapotranspiration Index. *Journal of Natural Resources*, 29(6): 1003–1016. (in Chinese)

Wang Q F, Shi P J, Lei T J et al., 2015. The alleviating trend of drought in the Huang-Huai-Hai Plain of China based on the daily SPEI. *International Journal of Climatology*, 35(13): 3760–3769. doi: 10.1002/joc.4244

Wang Q F, Wu J J, Lei T J et al., 2014. Temporal-spatial characteristics of severe drought events and their impact on agriculture on a global scale. *Quaternary International*, 349(10): 10–21. doi: 10.1016/j.quaint.2016.06.021

Wang Wei, Wang Wenjie, Li Junsheng et al., 2010. Remote sensing analysis of impacts of extreme drought weather on ecosystems in southwest region of China based on normalized difference vegetation index. *Research of Environmental Sciences*, 23(12): 1447–1455. (in Chinese)

Xiong Guangjie, Zhang Bokai, Li Chongyin et al., 2013. Characteristics of drought variations in Southwest China in 1961–2012 based on SPEI. *Advances in Climate Change Research*, 9(3): 192–198. (in Chinese)

Xu Dongfu, Li Dongliang, Qu Qiaona et al., 2013. The spatio-temporal variation of autumn dry-wet condition in southwest China and the analysis of its possible causes. *Journal of Tropical Meteorology*, 29(4): 570–580. (in Chinese)

Yang Hui, Song Jie, Yan Hongming, 2012. Cause of the severe drought in Yunnan province during winter of 2009 to 2010. *Climatic and Environmental Research*, 17(3): 315–326. (in Chinese)

Yang Jinhu, Zhang Qiang, Wang Jinsong et al., 2015. Extreme and persistent feature of drought and flood of Southwest China in past 60 years. *Scientia Geographica Sinica*, 35(10): 1333–1340. (in Chinese)

Yang Xiaojing, Zuo Depeng, Xu Zongxue, 2014. Characteristics of drought and floods analyzed using the Standardized Precipitation Index in Yunnan province during the past 55 years. *Resources Science*, 36(3): 473–480. (in Chinese)

Yao Yubi, Zhang Qiang, Wang Jinsong, 2015. Temporal-spatial abnormity of drought for climate warming in Southwest China. *Resources Science*, 37(9): 1774–1784. (in Chinese)

Yevjevich V M, 1969. An objective approach to definitions and investigations of continental hydrologic drought. Journal of Hydrology, 7(3): 353. doi: 10.1016/0022-1694(69)90110-3

Yin Han, Li Yaohui, 2013. Summary of advance on drought study in Southwest China. *Journal of Arid Meteorology*, 31(1): 182–193. (in Chinese)

Zargar A, Sadiq R, Naser B et al., 2011. A review of drought indices. *Environmental Reviews*, 19 (1): 333–349. doi: 10.1139/a11-013

Zhang Hongli, Zhang Qiang, Liu Xiaoyun, 2016. Study on the main factors of aridity in Hetao area of North China. *Climate Change Research*, 12(1): 20–27. (in Chinese)

Zhu Guofeng, Qin Dahe, Tong Huali 2016. Variation of thornthwaite moisture index in Hengduan Mountains, China. *Chinese Geographical Science*, 26(5): 687–702. doi: 10.1007/s11769-016-0820-3

Zuo Dongdong, Hou Wei, Yan Pengcheng et al., 2014. Research on drought in southwest China based on the theory of run and two-dimensional joint distribution theory. *Acta Physica Sinica*, 63(23): 1–12. (in Chinese)