



Spatial and Temporal Evolution Characteristics of Drought in Yunnan Province from 1969 to 2018 Based on SPI/SPEI

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Abstract The objective of this article is to describe the effect of precipitation and temperature on the drought characteristics of Yunnan province in China. The rainfall and temperature data from 10 national meteorological stations in Yunnan province during 1969 to 2018 were used to investigate the spatial and temporal evolution of drought in Yunnan province and the difference of drought index based on Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) at nearly 50a different time scales. The results showed that Yunnan province had a frequent alternation of drought and flood, and the larger the time scale, the gentler the SPI and SPEI changes. The recent 50a drought mainly occurred in 1980–1982, 1988–1990, 2003–2007, and 2010–2015, and there was continuous drought and the duration was prolonged. The changes of SPI and SPEI showed a downward trend in different seasons. The linear slopes of SPI and SPEI in spring, summer, autumn, and winter were -0.0064 , -0.0088 , -0.0057 and -0.0111 , respectively, and the drought trend was the most serious in winter. Continuous spring drought occurred in 2009–2010 and 2012–2014. The SPEI values in 2009–2010 and 2012–2014 were -0.80 , -0.64 , -0.75 , -1.23 , and -1.17 ,

respectively. The spatial distribution of drought frequency in Yunnan province was greatly different, and its distribution rule was more in the north and east, less in the south and west. The drought frequency in Zhaotong (northeast Yunnan) was the highest at 36.53%, the drought frequency in Deqin and Lijiang (northwest Yunnan) were 33.11% and 33.28%, and the drought frequency in Kunming (central Yunnan) Lincang, Lancang, and Simao (southwest Yunnan) were 29.35%, 30.73%, 32.77%, and 28.35%, respectively. This study provided a scientific basis for revealing the spatial and temporal variation rules, evolution trends, regional drought, and drought impact assessment and risk management of drought in Yunnan province.

Keywords Standardized precipitation index · Standardized precipitation evapotranspiration index · Multiple time scales · The spatial and temporal evolution of drought and Yunnan province

1 Introduction

Drought is a kind of complex natural disaster with long duration and wide coverage, which brings huge impact and loss to human life and agricultural production. Influenced by both natural changes and human activities, the global climate is undergoing a significant change characterized by warming (Dai 2011; Dai 2013). As the global climate continues to warm, the frequency and intensity of extreme climate events such as drought are gradually increasing. While drought is aggravated in arid and semi-arid areas in

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northern China, drought is aggravated in rainy areas in southern China (Liu et al. 2012; Zhang et al. 2016). From the autumn of 2009 to the spring of 2010, southwest China suffered the worst drought in a hundred years, which had a huge impact on agricultural production, ecological environment, and economic society (The Ministry of Water Resources of People's Republic of China 2010), and was of great significance to Yunnan province's adaptation to climate change and disaster prevention and reduction decision (Zhang et al. 2015). The study on the spatial and temporal distribution characteristics of regional meteorological factors and meteorological drought index and the reasonable estimation of their change trend (Dong et al. 2008) is of great significance for the research on water resource management and flood and drought disaster monitoring under the current climate change background.

Drought index can be used to describe the drought characteristics of different drought index of the applicable area and time are different; it serves as the main tool for monitoring and describing drought (Xu et al. 2017), such as Palmer drought severity index (PDSI) (Palmer 1965), the standardized precipitation index (SPI) (McKee et al. 1993), the composite meteorological drought index (CI) (Zhang et al. 2006), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), and so on. They are used in drought analysis at home and abroad. SPI is widely used because it requires fewer parameters to calculate and can better reflect drought intensity and duration, and use the same drought index to reflect drought conditions on different time scales, but SPI does not consider the influence of temperature, evapotranspiration, and other factors (Manatsa et al. 2010; Wang et al. 2014; Zhou et al. 2013). Vicente-Serrano (Vicente-Serrano et al. 2010) introduced potential evapotranspiration terms based on SPI in 2010 and proposed the standardized precipitation evaporation index (SPEI), which not only retained the advantages of SPI in multiple time scales, but also considered the impact of temperature on drought, which was widely used in drought research in recent years (Meza 2013; López-Moreno et al. 2013; Potop and Možný 2014; Törnros and Menzel 2014). Shaowei Zhuang (Zhuang et al. 2013) studied the application of SPEI in China, Lin Wang (Wang and Chen 2014) studied the applicability of SPEI to drought in China, and the results showed that SPEI had good applicability in China and could accurately characterize the drought conditions. Guifen Peng (Peng et al. 2009) analyzed the characteristics of arid climate in Yunnan and believed that Yunnan was most prone to drought in late spring and early summer, and

the drought duration and intensity were aggravated. Pingwei Zhao (Zhao et al. 2017) conducted seasonal successive drought analysis on meteorological data in southwest Yunnan from 1961 to 2013 based on SPI and SPEI, and Zhongyan Huang (Huang et al. 2013) conducted applicability analysis on agricultural drought monitoring and evaluation in Yunnan province from 2009 to 2010 based on several drought indicators. Yunnan province is located in the southwest of China. Its complex topography and special climate characteristics lead to the difference in the spatial and temporal distribution of drought. SPI and SPEI at multiple time scales (1, 3, 6, 12, and 24 months) were calculated, and seasonal SPI and SPEI were analyzed to make a comparative analysis of the drought characteristics in Yunnan province, so as to reveal the spatial and temporal variation rules and evolution trends of drought and provide scientific basis for regional drought and drought impact assessment and risk management.

2 Materials and Methods

2.1 Study area

Yunnan province (20°8'32"–29°15' 8" N, 97°31'39"–106°11'47"E) is located in southwest China, the tropic of cancer across the south. The province belongs to the low-latitude plateau, because of the influence of the atmospheric circulation, winter season by dry continental risk control system, humid summer prevailing Marine monsoon, belongs to subtropical plateau monsoon climate. The regional difference and vertical change of climate are very obvious, the annual temperature difference is small, the daily temperature difference is big, and the dry and wet season is distinct and distributed unevenly. The entire province average annual rainfall is 560.00–2300.00 mm, annual average temperature is 6.90–27.10 °C, and the wet season is from May to October, in which precipitation accounts for about 85.00% for the year, and the dry season is from November to April the following year, 15.00% of the annual rainfall (Liu et al. 2018). *China Meteorological Disaster Dictionary* (volume of Yunnan) (Wen and Liu 2006) divided the drought-stricken areas in Yunnan province into light drought-stricken areas, medium drought-stricken areas, and severe drought-stricken areas. In this article, meteorological stations in light, moderate, and severe drought areas were selected to analyze the drought characteristics of Yunnan province.

2.2 Data source and processing

The data came from China meteorological science data sharing service network (<http://data.cma.cn/>).

This study sorted out the monthly ground observation data of 10 national basic meteorological stations in Yunnan province from 1969 to 2018, mainly using data such as precipitation and average temperature. The distribution of meteorological stations in Yunnan province is shown in Fig. 1, and the meteorological station information is shown in Table 1.

2.3 Research Methods

2.3.1 SPI Calculation Method

We assumed that the precipitation change is subject to Γ distribution function and calculated in a certain period of time after Γ distribution probability, then carried out normal standardized processing, and finally to standardize precipitation cumulative frequency distribution to divide the drought grade (Li et al. 2016), which could be in different period precipitation to quantitatively characterize the lack of a degree. The construction process of the SPI was as follows.

We assumed that a certain period of time precipitation was x , and the Γ distribution of probability density function of

$$f(x) = \frac{1}{\beta^\gamma \Gamma(\gamma)} x^{\gamma-1} e^{-x/\beta} \quad (x > 0) \tag{1}$$

In the equation, β —scale parameters, γ —shape parameters. β and γ can be obtained by the maximum likelihood estimation method, that is,

$$\hat{\gamma} = \frac{1 + \sqrt{1 + \frac{4C}{3}}}{4C} \tag{2}$$

$$\hat{\beta} = \frac{\bar{x}}{\gamma^\wedge} \tag{3}$$

$$C = \lg \bar{x} - \frac{1}{n} \sum_{i=1}^n \lg x_i \tag{4}$$

In the equation, x_i —precipitation data samples, \bar{x} —climatological means of precipitation, and n —length of the calculation sequence.

Fig. 1 Distribution of meteorological stations in Yunnan province

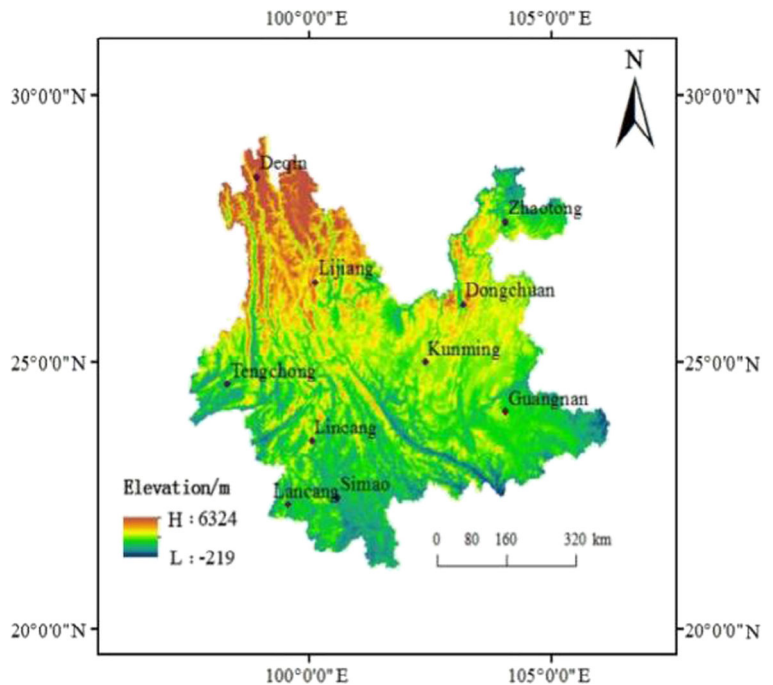


Table 1 Meteorological station information of Yunnan province

Weather station	Serial number	Longitude/(°)	Latitude/(°)	Elevation/m
Deqin	56,444	98.92	28.48	3319.0
Zhaotong	56,586	104.05	27.63	880.4
Lijiang	56,651	100.13	26.51	1001.3
Dongchuan	56,688	103.17	26.10	1254.1
Tengchong	56,739	98.30	24.59	1695.9
Kunming	56,778	102.39	25.02	1888.1
Lincang	56,951	100.08	23.53	1502.4
Lancang	56,954	99.56	22.34	1054.8
Simao	56,964	100.58	22.47	1302.1
Guangnan	59,007	105.07	24.05	1249.6

After determining the relevant parameters, the probability that the random variable x is less than x_0 can be calculated for the precipitation x_0 in a certain year:

$$F(x < x_0) = \int_0^{\infty} f(x) dx \tag{5}$$

$$F(x = 0) = m/n' \tag{6}$$

In the equation, m —a sample with 0 precipitation, and n —total sample size. To normal standardized processing of Γ probability distribution, Eqs. (5) and (6) will obtain probability value generation into the standardized normal distribution function:

$$F(x < x_0) = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-x^2/2} dx \tag{7}$$

The approximate solution of Eq. (7) can be obtained as follows:

$$SPI = S \frac{t - (c_2t + c_1)t + c_0}{[(d_3t + d_2)t + d_1]t + 1} \tag{8}$$

$$t = \sqrt{\ln \frac{1}{F^2}} \tag{9}$$

In the equation, F —probability of precipitation distribution associated with Γ function, S —probability density plus or minus coefficient, and $c_0, c_1, c_2, d_1, d_2, d_3$ —distribution function is converted to a cumulative frequency simplified solution formulas of approximate calculation:

$$F > 0.5, S = 1; F \leq 0.5, S = -1. \\ c_0 = 2.515517, c_1 = 0.802853, \\ c_2 = 0.010328, d_1 = 1.432788, \\ d_2 = 0.189269, d_3 = 0.001308.$$

2.3.2 SPEI Calculation Method

The SPEI replaces the monthly precipitation calculated by SPI with the monthly water deficit (the difference between monthly precipitation and monthly potential evaporation). Monthly potential evaporation was calculated by the Thornthwaite method. Unlike SPI based on Γ distribution, SPEI is based on the frequency value of the log-logistic distribution. The specific calculation process was as follows:

1. Calculate the monthly potential evaporation P_E

$$P_E = 16K \left(\frac{10T}{I} \right)^m \tag{10}$$

In the equation, P_E —potential monthly evaporation (mm), K —correction coefficient, T —monthly average temperature (°C), I —annual heat index, m —constant.

2. Calculate monthly losses D_i

$$D_i = P_i - P_E \tag{11}$$

In the equation, P_i —monthly rainfall (mm), D_i —monthly moisture deficit (mm), i —months.

3. Calculate the probability distribution of water deficit-based on the log-logistic probability distribution function:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} \left[1 + \left(\frac{x-\gamma}{\alpha}\right)^\beta\right]^{-2} \tag{12}$$

In the equation, $f(x)$ —probability density function, x —the independent variable, α , β , and γ —scale, shape, and position parameters.

The calculation formula was as follows:

$$\beta = \frac{2\omega_1 - \omega_0}{6\omega_1 - \omega_0 - 6\omega_2} \tag{13}$$

$$\alpha = \frac{(\omega_0 - 2\omega_1)\beta}{\Gamma\left(1 + \frac{1}{\beta}\right)\Gamma\left(1 - \frac{1}{\beta}\right)} \tag{14}$$

$$\gamma = \omega_0 - \alpha\Gamma\left(1 + \frac{1}{\beta}\right)\Gamma\left(1 - \frac{1}{\beta}\right) \tag{15}$$

In the equation, ω_0 , ω_1 , and ω_2 —the probability weights;

$$\omega_s = \frac{1}{n} \sum_{i=1}^n \left(1 - \frac{l-0.35}{n}\right)^s X_l \quad (s = 0, 1, 2). \tag{16}$$

In the equation, X_l —accumulated water deficit, $l=1, 2, \dots, n (n \in \mathbb{N})$.

The log-logistic probability distribution function is as follows:

$$F(x) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)^\beta\right]^{-1} \tag{17}$$

4. Normalize $F(x)$, $f = 1 - F(x)$,

$$SPEI = \begin{cases} W - \frac{c_0 + c_1 W + c_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} & (f \leq 0.5) \\ \frac{c_0 + c_1 W + c_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} - W & (f > 0.5) \end{cases} \tag{18}$$

$$W = \begin{cases} \sqrt{-2\ln f} & (f \leq 0.5) \\ \sqrt{-2\ln(1-f)} & (f > 0.5) \end{cases} \tag{19}$$

SPI and SPEI have the characteristics of multiple time scales, and SPI and SPEI at 5-time scales of 1, 3, 6, 12 and 24 months are calculated, which are represented by SPI-1, SPI-3, SPI-6, SPI-12, SPI-24, SPEI-1, SPEI-3, SPEI-6, SPEI-12, and SPEI-24, respectively. According to SPI and SPEI drought grading standards formulated by China meteorological administration (Chinese Academy of Meteorological Sciences, National Meteorological Center, Division of Disaster Prediction and Mitigation, Chinese Academy of Meteorological Sciences 2017), the classification of drought grades are shown in Table 2.

3 Results and Analysis

3.1 Variation Characteristics of SPI and SPEI Sequences at Different Time Scales

SPI and SPEI have multi-scale characteristics, which can accurately reflect the drought and flood situation in Yunnan province. Using the observed meteorological data from 1969 to 2018, we calculated SPI and SPEI multi-time-scale sequence value changes (Fig. 2). As can be seen from Fig. 2, the cycles and amplitudes of different time scale curves are different. Affected by short-term precipitation and temperature changes, the shorter the time scale, the more drastic SPI and SPEI changes, and the more frequent and larger the fluctuation around the 0 value indicating the frequent alternation of drought and flood in Yunnan province. With the increase of time scale, the changing trend of the two indexes tended to be gentle, the interannual change characteristics were obvious, and the duration of the

Table 2 SPI and SPEI drought classification criteria

Drought grade	SPI	SPEI
Wet	0.5 < SPI	0.5 < SPEI
No dry	-0.5 < SPI ≤ 0.5	-0.5 < SPEI ≤ 0.5
Light drought	-1.0 < SPI ≤ -0.5	-1.0 < SPEI ≤ -0.5
Moderate drought	-1.5 < SPI ≤ -1.0	-1.5 < SPEI ≤ -1.0
Severe drought	-2.0 < SPI ≤ -1.5	-2.0 < SPEI ≤ -1.5
Extreme drought	SPI ≤ -2.0	SPEI ≤ -2.0

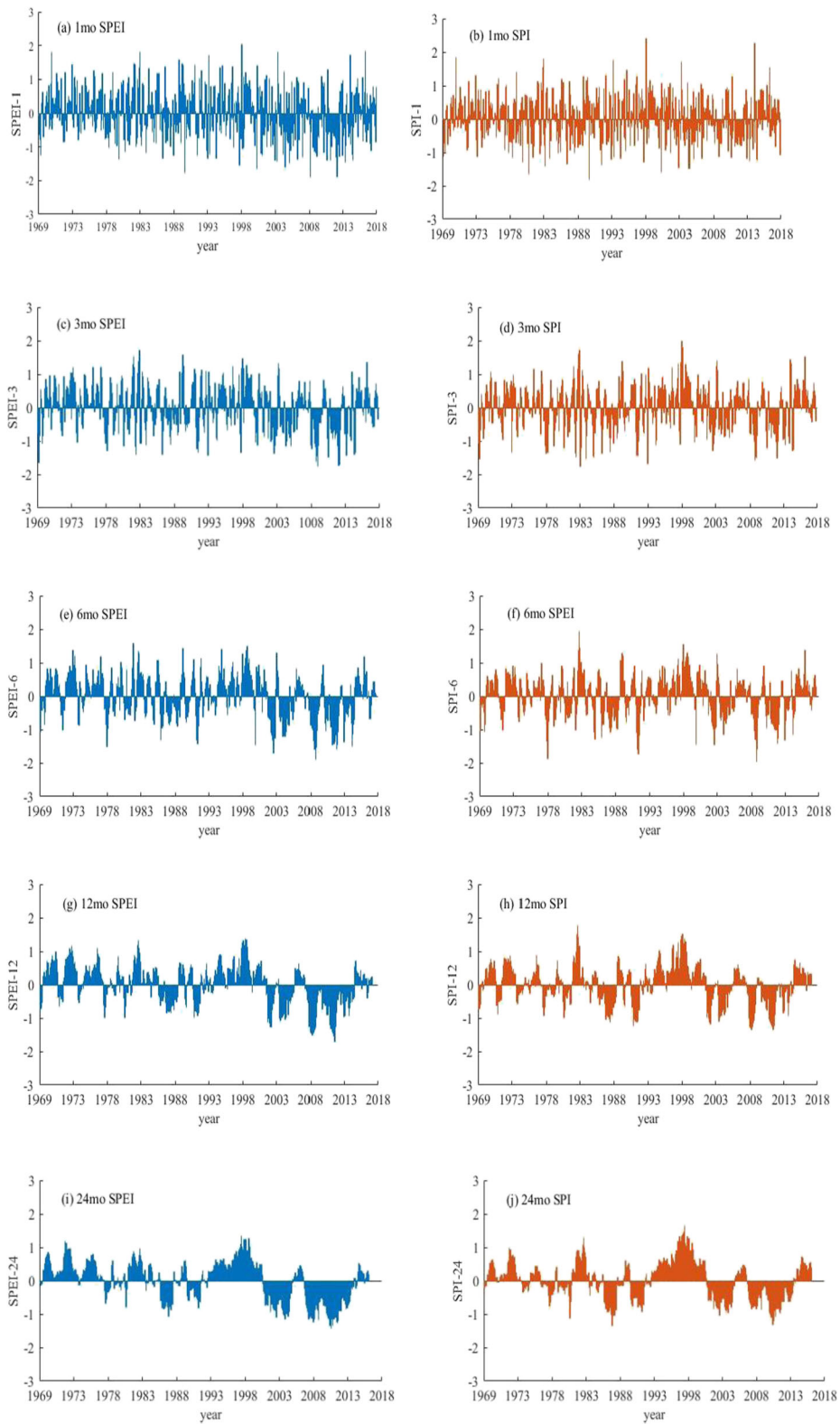


Fig. 2 SPEI and SPI changes at different time scales in Yunnan province from 1961 to 2018

dry/wet stage increased accordingly, which reflected the long duration of drought.

Figure 2a and b respectively represent SPI and SPEI time series values at 1-month scale, and SPI-1 and SPEI-1 fluctuate sharply along with the 0 value, reflecting the influence of monthly precipitation on the degree of drought. Taking 2000 as the dividing line, according to SPI value analysis, it is found that before 2000, there were 59 months of light drought in Yunnan province, 17 months of moderate drought, and 2 months of severe drought, with the frequency of 15.86%, 4.57%, and 0.54% respectively, and the drought frequency of 21.00%. After 2000, there were 45 months of light drought, 13 months of moderate drought, and 1 month of severe drought, with the frequency of 19.74%, 5.70%, and 0.44% and the drought frequency of 25.88%. Comparative analysis SPEI calculated that before 2000, there were 59 months of light drought, 16 months of moderate drought and 2 months of severe drought in Yunnan province, with the frequency of 15.86%, 4.30%, and 0.54%, respectively, and drought frequency of 20.70%. After 2000, there was a light drought for 49 months, moderate drought for 26 months, and the severe drought for 4 months, with the frequency of 21.49%, 11.40%, and 1.75% and drought frequency of 34.65%. SPI and SPEI drought both reflect the aggravation of drought in Yunnan province, especially after 2000, when the drought frequency increased significantly.

Figure 2c–f represents SPI and SPEI time series values at 3- and 6-month scales, respectively. Based on SPEI values of 3-month time scale, during 1969–2018, there were 145 seasonal droughts in Yunnan province, with a drought frequency of 24.25%, including 96 light, 43 moderate, and 6 severe ones, with a frequency of 16.05%, 7.19%, and 1.00%, respectively. The SPI/SPEI change curve at the 6-month scale has a longer fluctuation period than that at the 3-month scale and can reflect the change of dry and wet seasons. According to the SPI and SPEI curve variation diagram of 6-month time scale in Fig. 2e, f, Yunnan province was in a relatively wet period from 1995 to 2002, and then entered a dry period after 2003, and the drought was aggravated. Through SPEI sequence values, the frequency of drought in the last 50a dry season in Yunnan province was 20.95%, of which the frequency of light drought, moderate drought, and severe drought were 14.86%, 4.39%, and 1.69%, respectively. The frequency of light drought, moderate drought, and severe drought in the wet season was

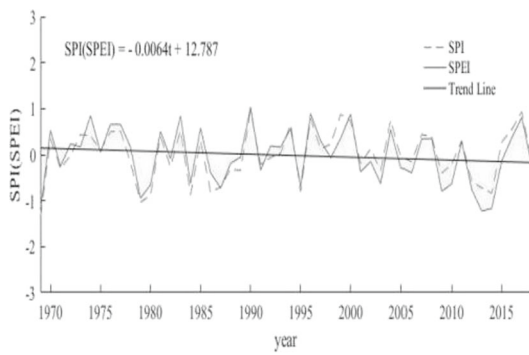
17.06%, 7.36%, and 0.67%, respectively. As the period of precipitation concentration, the frequency of drought in the wet season was as high as 25.08%, indicating that the precipitation in the wet season decreased and drought occurred frequently in Yunnan province.

Figure 2g–j are SPI and SPEI change curves at 12-month and 24-month scales respectively, indicating that there is no significant difference between the time variation characteristics of the two indexes. In Yunnan province, the obvious wet period in the recent 50a period was mainly concentrated in four periods during the drought period, which were 1980–1982, 1988–1990, 2003–2007, and 2010–2015, respectively, indicating that the drought frequency increased and the duration was longer and longer, and the drought severity was aggravated. In particular, since 2000, the number of dry years in Yunnan province has increased significantly and there has been continuous drought, which has seriously affected the growth of crops and led to the decline of their yields. In 2010, the severe drought in southwest China caused huge economic losses to agricultural production in Yunnan province, as well as ecological and environmental problems such as water shortage and river cut off. The wet periods were mainly concentrated in 1974–1975 and 1995–2002. By the drought index at the 24-month scale, the SPI average in 1974–1975 was 0.56 and the SPEI average was 0.67. From 1995 to 2002, the SPEI average was 0.54, and the SPI average was 0.64, both at a wetting level. After 2003, there was no concentrated humid year, which indicated that the degree of drought in Yunnan province was further intensified, and there was a trend of further drought.

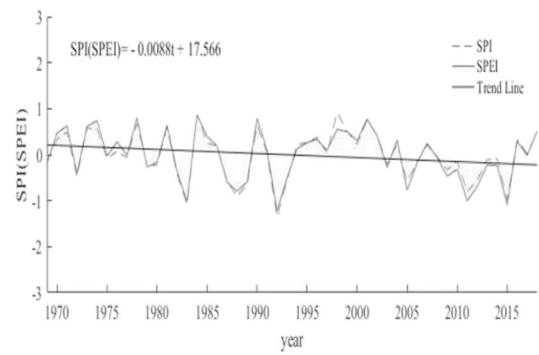
3.2 Variation Characteristics of SPI and SPEI in Different Seasons

A year is divided into four seasons according to the criteria of climatic seasons: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February the following year). Figure 3 showed SPI and SPEI change curves in different seasons in Yunnan province from 1969 to 2018.

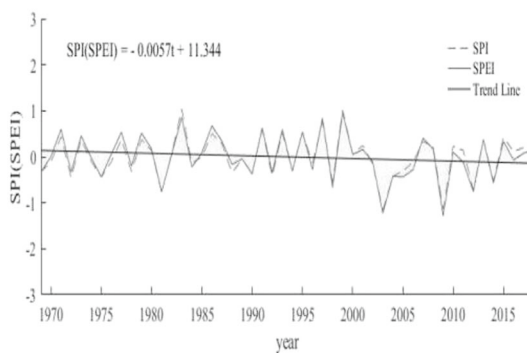
Figure 3 showed that SPI and SPEI had basically the same trend of change and both show a downward trend. The linear slopes of Fig. 3a–d are -0.0064 , -0.0088 , -0.0057 and -0.0111 , respectively, indicating that Yunnan province has a trend of drought in spring, summer, autumn, and winter and the most severe trend of



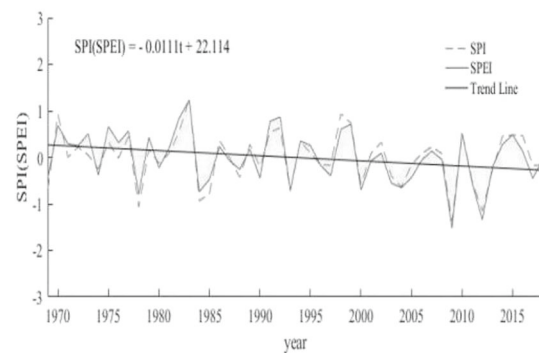
(a) Spring



(b) Summer



(c) Autumn



(d) Winter

Fig. 3 SPI and SPEI changes in different seasons in Yunnan province from 1969 to 2018

drought in winter. The rainy season in Yunnan province is from May to October, and the dry season is from November to the next April; it is prone to flood and the dry season is often dry.

Drought of Yunnan has obvious seasonal, Fig. 3a spring SPI and SPEI variation in Yunnan province in 1969–2018, we can observe that in 2000 before the spring drought situation of Yunnan province in light drought and drought, SPI and SPEI value is between -1.5 and -0.5 ; the condition of drought year is respectively in 1969, 1979, 1980, 1987, and 1995, and the SPI value respectively was 1.37, 1.04, 0.88, 0.71, and 0.80. SPEI values were -1.19 , -0.95 , -0.73 , and -0.69 , respectively. After 2000, the degree of spring drought increased, and there were consecutive drought events from 2009 to 2010, and from 2012 to 2014, the degree of drought increased year by year. SPEI values in 2009 and 2010 were -0.80 and -0.64 respectively, which were classified as light drought according to the degree

of drought. SPEI values in 2012, 2013, and 2014 were -0.75 , -1.23 , and -1.17 , respectively. The drought condition in 2012 was light drought, and the average annual drought in 2013 and 2014 was moderate drought. The reason is that the spring (March to May) is the dry season, when the southwest monsoon and the southeast monsoon have a very small impact on Yunnan province, with little precipitation and easy to form a drought. With global warming, the temperature increases and the precipitation decreases; it could aggravate the drought in Yunnan province.

Yunnan province is in the rainy season in summer, and the precipitation increases obviously. As can be seen from Fig. 3b, the peak years of summer drought in Yunnan province were 1983, 1988, and 1992, respectively, with SPI values of -1.09 , -0.90 , and -1.36 , and corresponding SPEI values of -1.02 , -0.80 , and -1.23 , respectively. During the period from 2000 to 2010, the drought condition in summer in Yunnan

province improved, but after 2010, the drought frequency in summer increased, a moderate drought occurred in 2011 and 2015, and light drought occurred in 2012. The reason for the drought is that Yunnan province is affected by both the southwest monsoon and the southeast monsoon in summer. The strength of the monsoon and the arrival time of the monsoon affect the rainfall and temperature of Yunnan province. From the global scale analysis, the El Niño/Southern Oscillation (ENSO) will affect the global atmospheric circulation and lead to the global climate abnormal changes. In the El Niño year, the large area of Yunnan province will be affected, resulting in high temperature, reduced precipitation, and the occurrence of drought.

As shown in Fig. 3c, the linear slope of the drought index in the autumn of nearly 50a in Yunnan province is the smallest, -0.0057 , indicating that the autumn is less affected by drought, the trend of drought is the least significant, and the change curve is relatively flat. The special years are 1981, 2003, and 2009, and the SPEI values are -0.77 , -1.16 , and -1.29 , respectively. The drought degree is light drought, medium drought, and medium drought respectively. The reason for the low frequency of drought in autumn is that the rainy season rainfall in Yunnan province is mainly from August to October, and the increase of rainfall and rainfall intensity makes the autumn climate humid and less affected by drought.

According to Fig. 3d, the linear slope of SPI and SPEI in winter is -0.0111 , indicating that the winter drought trend in Yunnan province is the most significant in the four seasons. In the winter of 1979, the SPI and SPEI values were -1.07 and -0.80 respectively at a mutation point, belonging to the drought condition. The other mutation point was in the winter of 1993, and SPI and SPEI values were -0.73 and -0.71 respectively, belonging to light drought. Around 2010, the drought intensity intensified, and SPEI values in 2009 and 2012 were -1.52 and -1.34 , both reaching the moderate drought level. The reasons are as follows: Yunnan province has a complex topography with many low mountains and hills and is located in the southeast edge of the Tibetan plateau. In winter, Yunnan-Guizhou plateau is mainly affected by the quasi-stationary front of Kunming, and the cold and warm air near the front is strongly convective, resulting in less rain after the front and sufficient sunshine before the front, with less rainfall and drought.

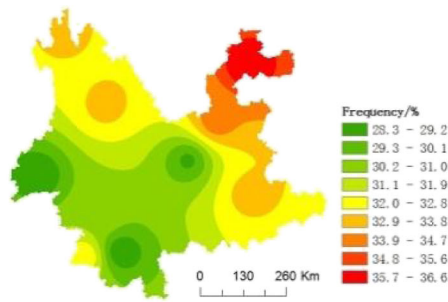
3.3 Spatial Characteristics of Drought in Yunnan Province

With the SPEI value of 12-month scale, the frequency of nearly 50a drought in Yunnan province was calculated, and the spatial distribution map of different degrees of interannual drought frequency in Yunnan province was made by using the inverse distance weight interpolation method (Fig. 4).

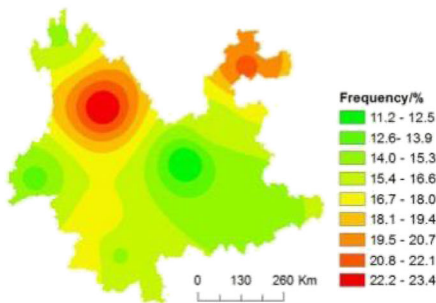
The drought frequency of nearly 50a in Yunnan province is basically 28.00–37.00%. The drought was most serious in Zhao Tong (Fig. 4a), with a drought frequency of 36.53% and a drought frequency of 34.42% in Dongchuan, indicating that the northeast region of Yunnan is a region with a high incidence of drought. The drought frequency of Deqin and Lijiang in northwest Yunnan is 33.11% and 33.28%, respectively. The drought frequencies of Kunming in central Yunnan and Lincang, Lancang and Simao in southwest Yunnan were 29.35%, 30.73%, 32.77%, and 28.35%, respectively. Compared with northeast Yunnan and northwest Yunnan, the degree of drought is lower in central and southwest Yunnan.

Figure 4b–e are spatial frequency distributions of light drought, moderate drought, severe drought, and extreme drought in Yunnan province for nearly 50a years. Lijiang (Fig. 4b) had the highest frequency of mild drought (23.43%). The second was Zhaotong (21.02%). The lowest drought frequency was 11.21% in Kunming. As shown in Fig. 4c, moderate drought mainly occurred in eastern, central, and northwestern Yunnan, with a high frequency of occurrence in Dongchuan, Guangnan, Kunming, and Deqin, with drought frequency of 12.63%, 11.02%, 11.21%, and 12.05%, respectively. The frequency of severe drought in Yunnan province is highest in the southeast Yunnan region (Fig. 4d). The frequency of severe drought in Guangnan, Zhaotong, Tengchong, Deqin, and Lancang are 7.14%, 5.31%, 5.43%, 4.92%, and 4.92%, respectively. The extreme drought condition belongs to the extreme weather in the atmospheric condition. The region with the highest occurrence frequency of extreme drought is southwest Yunnan (Fig. 4e). The drought frequency of Simao, Dongchuan, Kunming, Lancang, Zhaotong, Lijiang, and Guangnan is 4.58%, 2.65%, 2.38%, 2.21%, 2.04%, 2.04%, and 0.82%, respectively.

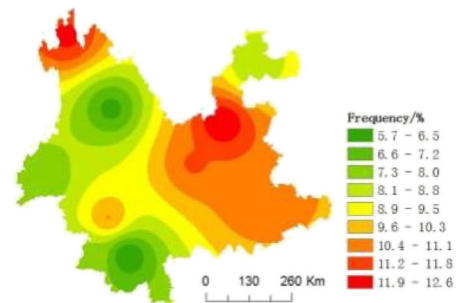
As can be seen from Fig. 4, the drought degree and frequency of Yunnan province are greatly different in space. Northeast Yunnan is a region prone to drought.



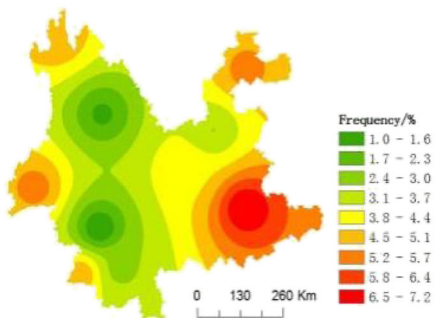
(a) Drought



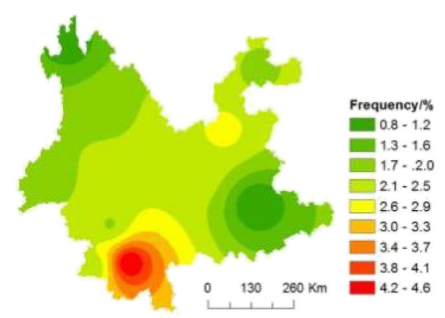
(b) Light Drought



(c) Moderate Drought



(d) Severe Drought



(e) Extreme Drought

Fig. 4 Spatial distribution of drought frequencies in different degrees in Yunnan province from 1969 to 2018

East and northwest Yunnan have a higher frequency of drought, while southwest Yunnan has a lower frequency

of drought. The reason is that the terrain of Yunnan province is low in the north and high in the south.

Secondly, the warm moist air flows are largely driven by the Indian Ocean southwest of Yunnan province and the influence of the Pacific Ocean southeast monsoon, and the complex landform forming more atmospheric circulation, the rainy season start time most gradually from south to north and from east to west, as a result, the temperature and precipitation in space is not balanced, and the mountains towards the foehn effect caused by the vertical circulation and plateau thermodynamic system affect the incidence of drought in southwest China, with strong local drought distribution, and it presents some complexity in space.

4 Conclusion

- (1) The shorter the time scale, the more frequent SPI and SPEI fluctuated around the 0 value and the larger the range was, which indicated the frequent alternation of drought and flood in Yunnan province. And the obvious drought periods of nearly 50a in Yunnan were mainly from 1980 to 1982, 1988 to 1990, 2003 to 2007, and from 2010 to 2015, which appeared even drought condition. In the dry season, the frequency of drought was 20.95%, among which the frequencies of light drought, moderate drought, and severe drought were 14.86%, 4.39%, and 1.69%, respectively. The frequency of light drought, moderate drought, and severe drought in the wet season was 17.06%, 7.36%, and 0.67%, respectively. As a precipitation concentration period, the drought frequency of the wet season is as high as 25.08%, indicating that the precipitation in the wet season in Yunnan province decreases and drought occurs frequently.
- (2) From 1969 to 2018, SPI and SPEI showed a downward trend in different seasons in Yunnan province. The linear slopes of SPI and SPEI in spring, summer, autumn, and winter were -0.0064 , -0.0088 , -0.0057 and -0.0111 , respectively, so the drought was aggravated and winter was the most severe. During 2009–2010 and 2012–2014, there was a continuous spring drought, and the drought was aggravated year by year. SPEI values in 2009 and 2010 were -0.80 and -0.64 , respectively. And the values in 2012, 2013, and 2014 were -0.75 , -1.23 , and -1.17 , respectively. In the summer of 1983, 1988, and 1992, there were dry peaks with SPI values of -1.09 , -0.90 , and -1.36 , respectively, and corresponding SPEI values of -1.02 , -0.80 and -1.23 , respectively.
- (3) There are great spatial differences in drought degree and frequency in Yunnan province. The frequency of drought in Yunnan province is 28.00 to 37.00%, and the spatial distribution of drought frequency is more in the north and east and less in the south and west. Northeast Yunnan Zhaotong drought is the most serious, the drought frequency was 36.53%, followed by 34.42% Dongchuan drought frequency, and Deqin and Lijiang in northwest Yunnan drought frequency of 33.11% and 33.28%, respectively. The drought frequencies of Kunming in central Yunnan and Lincang, Lancang, and Simao in southwest Yunnan were 29.35%, 30.73%, 32.77%, and 28.35%, respectively, relative to the northeast and northwest in Yunnan, and the central and southwest is the low degree of drought.

5 Discussion

Drought is mainly caused by climate change, in which precipitation and temperature are the direct influencing factors of drought. SPI and SPEI are based on these two factors and can eliminate the spatial and temporal differences of precipitation and reflect the spatial and temporal evolution characteristics of drought more accurately (Zhao et al. 2016). SPI and SPEI calculated values reflected that the drought period of nearly 50a in Yunnan province was mainly from 1980 to 1982, 1988–1990, 2003–2007, and 2010–2015. Through verification with historical drought records, the applicability of the two indexes to reflect the drought condition of Yunnan province was proved, which was consistent with the research results of Lin Wang (Wang and Chen 2014) and Binqian Li (Li et al. 2008). Yunnan province alternates between wet and dry with a 3–5-year oscillation cycle (Zhang et al. 2015; Huang et al. 2013), and the oscillation cycle has a time domain. In recent 50a years, the degree of annual drought intensifies, the frequency of spring drought is high, and the trend of winter drought is obvious, which is basically consistent with the results of Yan Han (Han and Jiang 2018), who analyzed the drought characteristics of Yunnan province and the determination of a typical drought year. In Yunnan province, the drought degree of drought frequency has

remarkable space differences; the distribution of drought frequency is more in the north and east and less in the south and west. The main reason is low terrain north of Yunnan province meteorological, and low mountain hills, and dry valley less rainfall and evaporation capacity are big, and the mountains towards the foehn effect and highland thermodynamic vertical circulation system, the formation of atmospheric circulation background of little rainfall and drought. Drought distribution has a stronger local area, presents some complexity in space, has to do with Shunping Qin (Qin et al. 2014), and the results are consistent.

This study provides a scientific basis for drought and drought impact assessment and risk management in Yunnan province and has guidance and practicability for application decision-making. SPI and SPEI as meteorological drought indices, while considering the problems, such as precipitation, evaporation temperature, and has good applicability to reflect regional drought conditions, but because of the weather, agriculture, water conservancy department different angle and focus of attention to the drought monitoring, SPI and SPEI are difficult to meet the real needs of different industries of the real-time drought monitoring. Therefore, drought monitoring research is still a long-term and urgent task.

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