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Research Article

Temporal-Spatial Characteristics of Drought in Guizhou Province, China, Based on Multiple Drought Indices and Historical Disaster Records

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Guizhou Province, China, experienced several severe drought events over the period from 1960 to 2013, causing great economic loss and intractable conflicts over water. In this study, the spatial and temporal characteristics of droughts are analyzed with the standard precipitation index (SPI), comprehensive meteorological drought index (CI), and reconnaissance drought index (RDI). Meanwhile, historical drought records are used to test the performance of each index at identifying droughts. All three indices show decreasing annual and autumn trends, with the latter particularly prominent. 29, 30, and 32 drought events were identified during 1960–2013 by the SPI, CI, and RDI, respectively. Continuous drought is more frequent in winter–spring and summer–autumn. There is a significant increasing trend in drought event frequency, peak, and strength since the start of the 21st century. Drought duration indicated by CI shows longer durations in the higher-elevation region of central and western Guizhou. The corresponding drought severity is high in these regions. SPI and RDI indicate longer drought durations in the lower elevation central and eastern regions of Guizhou Province, where the corresponding drought severity is also very strong. SPI shows an increasing trend in drought duration and drought severity across most of the regions of Guizhou. In general, SPI and RDI show an increasing trend in the western Guizhou Province and a decreasing trend in central and eastern Guizhou. Comparing these three drought indices with historical records, the RDI is found to be more objective and reliable than the SPI and CI when identifying the periods of drought in Guizhou.

1. Introduction

Drought, a water shortage phenomenon caused by natural precipitation anomalies, is one of the most serious natural disasters, causing economic losses globally. The American Meteorological Society classified droughts into four types: meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought [1]. Meteorological drought refers to water shortages caused by an imbalance in precipitation and evaporation. Drought disasters are a product of the coupling of the natural environmental and socioeconomic systems under specific time and space conditions [2]. Among different types of natural disasters, drought disasters are among those with the highest frequencies, widest

ranges of influence, longest durations, and greatest losses; drought disasters lead not only to food production reduction, water shortages, and deterioration of ecosystems and the environment, but also to death and the change of dynasties, given that they are an important factor in restricting sustainable social development [3]. The factors influencing drought disasters are complex since there are great uncertainties relating to the occurrence and development of drought disasters in both time and space.

Drought is one of the most frequent and widespread natural disasters in China, where the total average area of land periodically influenced by droughts is 2.1×10^7 hm^2 (annual average value from 1950 to 2013), of which 9.4×10^6 hm^2 (annual average value from 1950 to 2013) suffers drought disasters in any particular year. Meteorological droughts, as described above, can develop into agricultural droughts [4, 5]. In China, droughts cause an annual average of 2.5×10^6 hm^2 of no-harvest area (annual average value from 1989 to 2013) and 1.62×10^{10} kg of grain loss (annual average value from 1950 to 2013); droughts also cause 2.7×10^7 people (annual average value from 1991 to 2013) and 2.0×10^7 livestock (annual average value from 1989 to 2013) to have difficulty finding sufficient drinking water; together, these factors contribute to an annual average direct economic loss of 1.0×10^{11} Chinese Yuan (annual average value from 1950 to 2013, http://www.mwr.gov.cn/sj/tjgb/zgshzhgb/201612/t20161222_776092.html) [6]. The abovementioned information indicates that China as a major agricultural country suffered severe meteorological droughts which caused great economic losses [7]. Drought is the hot spot of research for a long time. Zhai et al. [8] found that a significant dryness trend changes from the southwest to the northeast of China. In the early twenty-first century, the most severe droughts were located in the Southwest of China covering areas around 0.7 million km^2. Yu et al. [9] found that the severe and extreme droughts become more serious since late 1990s for the entire China via examining drought characteristics such as long-term trend and intensity duration. Meanwhile, the drought-prone regions in Northeast China, Southwest China, south China coastal region, and Northwest China were investigated by He et al. [7] and Ayantobo et al. [10]. Xu et al. [11] indicated that the three drought indices (SPI, RDI, and SPEI) have almost the same performances in the humid regions. However, SPI and RDI were more appropriate than SPEI in the arid regions. The Loess Plateau, Sichuan Basin, and Yunnan-Guizhou Plateau have significant dry trends, which is mainly caused by the significant decrease of precipitation. Liu et al. [12] found that the return periods of meteorological drought are longer, with an average of 42.1 years in China. Liu et al. [13] investigated the return period of concurrent drought events is 11 years in the water source area and the destination regions of water diversion project. The probability of concurrent drought events may significantly increase during 2020 to 2050. Shen et al. [14] revealed that the drought probability and intensity are rising and the affected areas of all degrees of drought have an increasing trend during the last 50 years based on the SPEI in Song-Liao River Basin.

The Southwest is one of the regions of China most frequently affected by drought disasters, with droughts of different degrees of severity occurring in this region almost every year, including a severe drought covering a large area every 5–10 years [15]. From 2009 to 2012, the five provinces of Southwest China (Yunnan Province, Sichuan Province, Chongqing City, Guizhou Province, and Guangxi Province) suffered a severe drought [16, 17]. This severe drought, which affected ~8.0×10^6 hm^2 of arable land, led not only to a large reduction in crop production but also caused drinking water shortages for 25 million people and 18 million livestock; meanwhile, the drought caused total direct economic losses of more than 40 billion Chinese Yuan [16, 17]. This drought was the worst in Southwest China since meteorological observations began [18]. The increasing frequency of severe droughts in the Southwest demonstrates that droughts are spreading from northern to southwestern China [19].

Sun et al. [20] assessed the contributions of decadal potential evapotranspiration (PET) anomalies to drought duration and intensity which could exceed those of precipitation in Southwest China. Li et al. [21] identified 87 drought events including 9 extreme events using the daily composite drought index (CI) at 101 stations in Southwest China. The droughts are more frequent from November to next April, and the frequency and intensity of drought increased with a significant decrease in precipitation and increase in temperature. Gao et al. [22] found that the significant soil drying trend happened in autumn, which can be sustained to the next spring. Han et al. [23] showed that the eastern part of southwestern China had an extremely high drought risk, which was greater in the north than south. Recently, several extreme drought disasters have hit Guizhou Province, such as that from September 2009 to March 2010, which caused drinking water shortages for 4.85 million people, with 7.01×10^5 hm^2 of crops suffering from drought, and direct economic losses of 2.3 billion Chinese Yuan. A subsequent extreme summer drought in 2011 caused drinking water shortages for 5.5 million people and 2.8 million livestock, with 1.763×10^6 hm^2 of crops affected, resulting in an economic loss of 15.76 billion Chinese Yuan. Only two years later, the extreme summer drought of 2013 caused drinking water shortages for 2.645 million people and 1.12 million livestock, with 1.763×10^6 hm^2 of crops affected, causing an economic loss of ~9.64 billion Chinese Yuan [24–26].

Droughts are typically measured and quantified using drought indices; a variety of indices for different applications have been developed [27, 28]. Based on World Meteorological Organization (WMO) statistics, there are 55 commonly used categories of drought indices. Among these, the comprehensive meteorological drought index (CI), standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), and reconnaissance drought index (RDI) are widely used in various regions [21, 29–36]. At present, case studies of droughts in Guizhou Province are rare, with most such studies based on a single drought index [37, 38]. Furthermore, no study has validated these drought indices using historical disaster records, despite validation of the reliability of these indices being of great importance. This study aims at building a link between drought indices and real drought events in Guizhou Province, China.

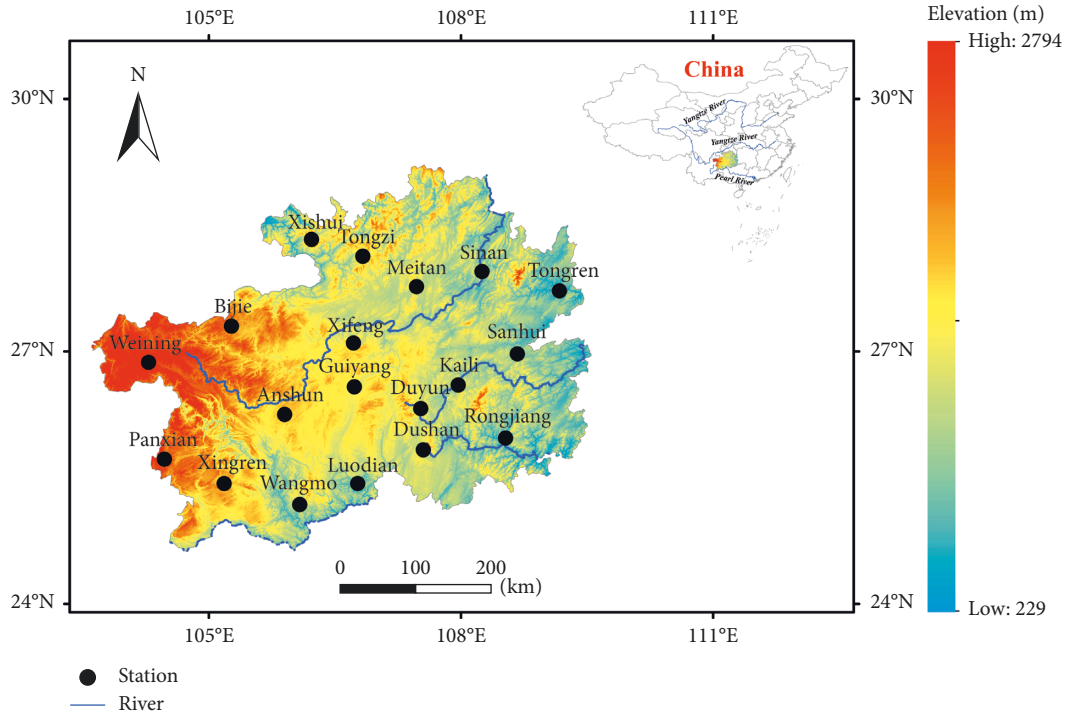

Figure 1: Location of meteorological stations in Guizhou Province.

2. Study Region and Data Resources

2.1. Study Region. Guizhou Province (103°36′–109°35′E; 24°37′–29°13′N), with an area of 176167 km^2, is located in the eastern Yunnan-Guizhou Plateau of China (Figure 1). The elevation of Guizhou Province ranges from 229 to 2794 m, higher in the west than that in the east of province [39]. The topography is dominated by plateau and mountains: carbonate rocks in the karst area are widespread and account for 62% of the total area of Guizhou Province. Guizhou has a humid subtropical monsoon climate with an annual mean temperature of 15°C and mean annual precipitation of 1400 mm. Over 70% of the annual rainfall occurs from May to September [39–41]. In general, the ecology and environment of Guizhou Province is extremely fragile, which causes frequent land-surface droughts, as illustrated by an old saying describing drought in Guizhou Province: "a drought every year, a mild drought every three years, a moderate drought every five years, a severe drought every decade."

2.2. Data Resources. The meteorological data for daily precipitation and pan evaporation (from January 1, 1959, to February 28, 2014) data set are used in this paper from the China Meteorological Data Sharing Service Network (http://data.cma.cn/) V3.0 version. Rigorous quality control had been conducted by China Meteorological Data Sharing Service Network before the data were released. The software used to detect and adjust shifts in the time series of daily precipitation and pan evaporation is RHtestsV3 and RHtests-dlyPrcp (http://etccdi.pacificclimate.org/software.shtml), respectively. Finally, 19 out of 32 national basic meteorological stations (no gaps exceeding two consecutive weeks) are selected for this study. It should be noted that some evaporation data (since 2002) were recorded with E601B equipment. The E-601B-type evaporator was installed for meteorological stations in China from 1985. The E-601B-type evaporation evaporator is recommended by the World Meteorological Organization (WMO). This instrument has the advantages of corrosion-resistant and stable thermal effect, which made the measurements more close to nature [42]. In order to ensure the continuity, uniformity, and reliability of records, a linear regression is therefore applied to calibrate evaporation data collected by E601B (2002–2014) to 20 cm evaporating dish data (1998–2001), according to previous studies [43, 44]. The elevation data (DEM) are from the Shuttle Radar Topography Mission (SRTM) with a resolution of 90 m, derived from the Geospatial Data Cloud of China (http://www.gscloud.cn/). The historical disaster records are derived from China Meteorological Disaster Yearbook (Guizhou volume) [45–51]. The information such as drought duration, severity, and peaks was extracted from the yearbooks according to the disaster statistics which were originally recorded by the local meteorological department. Seasons are classified based on meteorological divisions: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February), respectively. The distribution of meteorological stations, together with related information, is shown in Figure 1 and Table 1.

3. Methods

3.1. Drought Indices (SPI, CI, and RDI)

3.1.1. Standard Precipitation Index (SPI). The SPI was developed by McKee et al. [29]. Within a certain geographic

Table 1: Information of meteorological stations and average precipitation and 20 cm pan evaporation in 1960–2013.

Station	Longitude (°E)	Latitude (°N)	Elevation (m)	Pan precipitation (mm)	Evaporation (mm)	$P-C_V$	$E-C_V$
Anshun	105.9	26.25	1431.1	1310.1	1250.5	0.18	0.09
Bijie	105.27	27.3	1510.6	883.2	986.1	0.15	0.10
Duyun	107.52	26.32	969.1	1419.9	1239.1	0.17	0.08
Dushan	107.55	25.83	1013.3	1307.5	1201.4	0.14	0.09
Guiyang	106.73	26.58	1223.8	1099.6	1377.5	0.16	0.10
Kaili	107.97	26.6	720.3	1142.1	1347.8	0.18	0.09
Luodian	106.77	25.43	440.3	1142.1	1246.5	0.18	0.07
Meitan	107.47	27.77	792.2	1116.5	1052.6	0.15	0.10
Panxian	104.47	25.72	1800	1355	1599.1	0.18	0.12
Rongjiang	108.53	25.97	285.7	1181.6	1174.1	0.17	0.11
Sanhui	108.67	26.97	626.9	1102	1129.7	0.15	0.11
Sinan	108.25	27.95	416.8	1120.1	1148.4	0.19	0.10
Tongzi	106.83	28.13	972	1259.8	1198	0.14	0.09
Tongren	109.17	27.72	353.2	1008.4	1091.5	0.13	0.15
Wangmo	106.08	25.18	566.8	1222.2	1453.8	0.16	0.09
Weining	104.28	26.87	2237.5	889.7	1350.2	0.19	0.08
Xifeng	106.72	27.1	1112.1	1108.4	1282.5	0.15	0.12
Xishui	106.22	28.33	1180.2	1094.3	1002.3	0.14	0.10
Xingren	105.18	25.43	1378.5	1317.3	1517.1	0.15	0.09

Note. $P-C_V$, coefficient variation of precipitation; $E-C_V$, coefficient variation of pan evaporation.

Table 2: Classification of SPI, CI, and RDI.

SPI/CI/RDI value	Drought grades
Value ≤ -2.0	Extreme drought
$-2.0 <$ value ≤ -1.5	Severe drought
$-1.5 <$ value ≤ -1.0	Moderate drought
$-1.0 <$ value ≤ 0	Mild drought

area, the precipitation usually fluctuates regularly. If the precipitation is less than the average annual precipitation, a drought may therefore occur in this area. On the contrary, precipitation exceeding the annual average may induce flooding. The SPI has many advantages such as being dimensionless and standardized, working on multiple scales, and being easy to calculate. To calculate the SPI, a frequency distribution function is first constructed from a series of long-term precipitation observations. A gamma probability density function is then fitted to the series, and the cumulative probability of an observed precipitation is computed. The inverse normal (*Gaussian*) function, with a mean of 0 and a variance of 1, is then applied to transform the cumulative distribution to the standard normal distribution. Because the SPI is based on the cumulative probability of a given timescale, here the total amount of precipitation in the current month and previous i months ($i = 1, 2, 3, \ldots$) is used to calculate the SPI on a timescale of $i+1$ month. Here, SPI_{12} (1–12 monthly cumulative precipitation) represents annual timescales, and SPI_3 (3 monthly cumulative precipitation) represents seasonal timescales. Drought classification is shown in Table 2.

3.1.2. Comprehensive Meteorological Drought Index (CI). The comprehensive meteorological drought index (CI) is effective for meteorological drought monitoring and assessment [52]. Both 30 day (month scale) and 90 day (seasonal scale) standardized precipitation indices, combined with a 30 day relative humidity index, can be used to calculate a comprehensive meteorological drought index. Since the CI can indicate precipitation climate anomalies on both short (months) and long timescales (seasons) [52], this index is therefore suitable for meteorological drought monitoring and historical drought assessment. The first step of the calculation is as follows:

$$\mathrm{MI} = \frac{\left(P_{ij} - \mathrm{PET}_{ij}\right)}{\mathrm{PET}_{ij}}, \tag{1}$$

where MI is the relative moisture index in the recent 30 days, P_{ij} refers to the total amount of precipitation in the recent 30 days (unit: mm), and PET_{ij} is the total potential evapotranspiration in the recent 30 days (mm; here we use evaporation of a 20 cm evaporating dish). The CI is then calculated as follows:

$$\mathrm{CI} = a\mathrm{SPI}_{30} + b\mathrm{SPI}_{90} + c\mathrm{M}_{30}, \tag{2}$$

where SPI_{30} and SPI_{90} are the standardized precipitation indexes for 30 d and 90 d periods, respectively. M_{30} refers to the MI of 30 days. a, b, and c are set as 0.4, 0.4, and 0.8. In theory, the weight coefficients a, b, and c are from the average values above light drought levels of SPI_{30}, SPI_{90}, and MI_{30} divided by the smallest history of SPI_{30}, SPI_{90}, and MI_{30}, respectively (GBT 20481-2006 meteorological drought level) [52]. The drought classification scheme is displayed in Table 2.

3.1.3. Reconnaissance Drought Index (RDI). The drought detection index was proposed by Tsakiris et al. [31, 32] and takes into account the effects of precipitation and evapotranspiration on drought. The RDI has three modes of expression: the initial value RDI (α_0) is presented in an aggregated form using a monthly time step and calculated

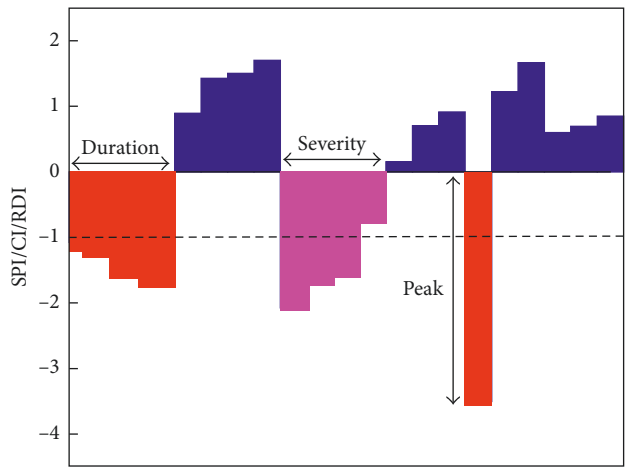

FIGURE 2: Definition of drought characteristics for SPI, CI, and RDI based on Run Theory.

for each month of a hydrological year or a complete year. The second expression is normalized RDI (RDI_n), and the third expression is standardized RDI (RDI_{st}). The initial value α_0 can be calculated with the following formula:

$$a_0^i = \frac{\sum_{i=1}^{12} P_{ij}}{\sum_{j=1}^{12} \mathrm{PET}_{ij}}, \quad i = 1, \ldots, N \quad \text{and} \quad j = 1, \ldots, 12, \tag{3}$$

where P_{ij} and PET_{ij} are precipitation and potential evapotranspiration (we use evaporation of the 20 cm evaporating dish) in jth month of ith hydrological year, respectively. N is the total number of years. Equation (3) can calculate the RDI for any period of the year.

The normalized RDI, RDI_n, is calculated using the following equation for each year, in which it is evident that the parameter $\overline{a}_0$ is the arithmetic mean of a_0 values calculated for the N years of data:

$$\mathrm{RDI}_n^{(i)} = \frac{a_0^{(i)}}{\overline{a_0}} - 1. \tag{4}$$

The standard RDI (RDI_{st}) is similar to the standard precipitation index (SPI) and is calculated as follows:

$$\mathrm{RDI}_{\mathrm{st}} k^{(i)} = \frac{y_k^{(i)} - \overline{y_k}}{\overline{\sigma_{yk}}}, \tag{5}$$

where $y_k^{(i)} = \ln(a_0^{(i)})$, $\overline{y_k}$ is the arithmetic mean of y_k, and σ_{yk} is the standard deviation of $y_k^{(i)}$.The drought classification scheme is shown in Table 2.

3.2. Drought Variables. According to McKee et al. [29] and Spinoni et al. [53], a drought event is defined as being when SPI, CI, and RDI values are lower than −1 (included in this month) to positive value (excluding this month), with at least two consecutive such months used to define drought events from 1960 to 2013 in this study. Drought duration-severity-area-intensity/frequency is widely used in drought research [8, 10, 11, 54]. The derived drought variables [54, 55] based on the Run Theory follow the definitions (Figure 2). Drought duration is defined as the number of months from the first month in which the indicator goes lower than −1 to the last month with a negative value before the indicator returns to positive values. Drought intensity is defined as the number of months in which the drought indicator remains lower than −1. Drought severity is defined as the sum of the monthly absolute values of the index when the index is ≤−1 over the period 1960–2013. Drought peak refers to the month in the "drought event" with the lowest value of the indicator [36].

3.3. Mann–Kendall Test. The Mann–Kendall (M-K) nonparametric statistical test method, proposed by Mann [56] and Kendall [57] and recommended by the World Meteorological Organization (WMO). The M-K test does not require samples to follow a certain distribution nor is affected by a few abnormal values. It is widely used in the data of nonnormal distribution of hydrology and meteorology due to its simplicity. Here, the M-K test is applied to analyze the temporal characteristics of SPI, CI, and RDI. For a time series, $X = \{x_1, x_2, \ldots, x_n\}$, where $n > 10$. The test statistic Z_{mk} is calculated as follows:

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{cases},$$

$$\text{where,} \quad S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \mathrm{sgn}(x_k - x_i),$$

$$\mathrm{Var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5)\right]}{18}, \tag{6}$$

where $\mathrm{Var}(S)$ is the variance of the statistic S; x_k and x_i are the sequential data values; m is the number of tied groups; t_i denotes the number of data points in the ith group; n is the length of the data set; and sgn $(x_k - x_i)$ is the sign function, determined as

$$\mathrm{sgn}(x_k - x_i) = \begin{cases} +1, & (x_k - x_i) > 0 \\ 0, & (x_k - x_i) = 0 \\ -1, & (x_k - x_i) < 0 \end{cases}. \tag{7}$$

For the statistic Z_{mk} value, $Z_{mk} > 0$ indicates that the time series has a rising (increasing) trend, while time series with $Z_{mk} < 0$ has a falling (decreasing) trend. Absolute values of $Z_{mk} \geq 1.65$, 1.96, and 2.58 are adopted, respectively, indicating significance levels of $\alpha = 0.1$, 0.05, and 0.01.

When the M-K test is further used to test the sequence mutation, the test statistic is different from the above Z_{mk}, by constructing a rank sequence:

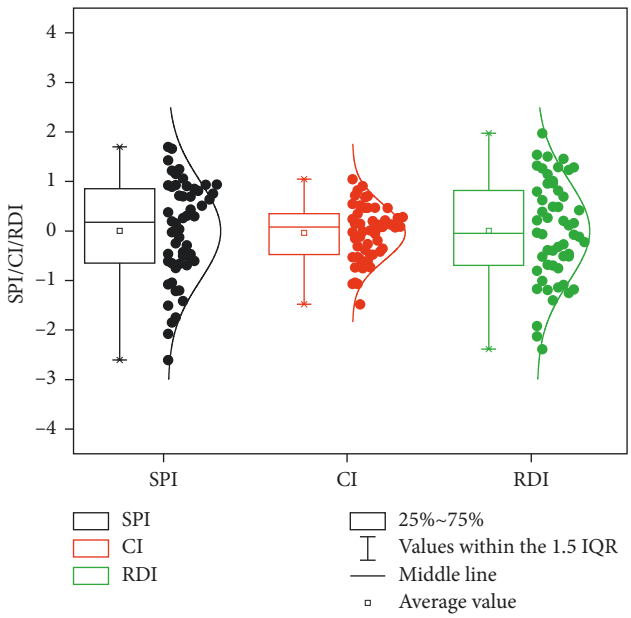

Figure 3: Box-plot line and normal distribution curve for SPI, CI, and RDI.

$$S_k = \sum_{i=1}^{i} \sum_{j}^{i-1} \alpha_{ij} \quad (k = 2,\ 3,\ 4, \ldots, n),$$

$$\alpha_{ij} = \begin{cases} 1 & x_i > x_j, \\ & 1 \le j \le i, \\ 0 & x_i < x_j, \end{cases}$$

$$\mathrm{UF}_k = \frac{[S_k - E(S_k)]}{\sqrt{\mathrm{Var}(S_k)}} \quad (k = 1,\ 2, \ldots, n), \tag{8}$$

$$E(S_k) = \frac{k(k+1)}{4},$$

$$\mathrm{Var}(S_k) = \frac{k(k-1)(2k+5)}{72},$$

where UF_k is a standard normal distribution and a significant level α is given. If there is a significant trend change, the time series x is arranged in reverse order and then is calculated according to the formula:

$$\mathrm{UB}_k = -\mathrm{UF}_k$$
$$k = n + 1 - k \quad (k = 1,\ 2, \ldots, n), \tag{9}$$

where UF_k is a positive sequence and UB_k is a reverse sequence. If UF_k exceeds 0, the sequence shows a rising trend, and a value of <0 indicates a falling trend. The rising or falling trend is significant when these parameters exceed the critical line. If the UF_k and UB_k curves intersect and the intersection is between the critical straight lines, the corresponding moment of intersection is defined as the moment when the mutation begins.

4. Results

4.1. Temporal Variability. Figure 3 shows the box-plot line and normal distribution curve for CI, SPI, and RDI. All three indices conform to normal distribution, and the distribution of drought indices is also very similar in the box-plot for SPI and RDI. The normal distribution of the CI is concentrated, and the box-plot reflects drought ranks' relative light. Figure 4 shows annual and seasonal SPI trends and the M-K test in Guizhou Province. Annual and seasonal Z values were, respectively, −2.33, −1.99, −0.39, −2.30, and −0.72, and all showed a decreasing trend. Annual, spring, and autumn trends were significant at the 0.05 significance level. The magnitude of the decreasing trend for the annual and autumn trends is larger, at −0.020/10a and −0.023/10a, respectively. As illustrated in Figure 4(a), the annual decreasing trend is significant in 1980–1990 and 2000–2013 at the 0.05 significance level. UF and UB intersect in 2006 and break through the boundary line in 2012-2013. In spring, UF and UB intersect in 1984 and break the boundary line in 1998–2001, 2007, and 2010–2013. In autumn, UF and UB intersect in 1986 and break the boundary line in 2003–2013, indicating a significant abrupt decrease in the trend. However, summer and winter mutations are not significant. According to the drought index, annual severe droughts or extreme droughts are found in 1966, 2009, 1989, and 2013. For seasons, severe or extreme droughts in spring are more often in 1979, 1986, 1988, 1991, and 2011, while in summer they are found in 1972, 1981, 2011, and 2013. For autumn, the severe or extreme droughts are found in 1969, 1978, 1992, 2002, and 2006. For winter, the years with severe or extreme winter droughts are 1978, 1985, 2009, and 2012.

Z values for annual and seasonal droughts were, respectively, −2.26, −0.66, −0.24, −2.69, and −1.51; all showed a decreasing trend, with the trend for annual and autumn timescales significant at the 0.05 significance level (Figure 5). The rate at which the trend decreases for annual and autumn timescales is larger, at −0.012/10a and −0.018/10a, respectively. As illustrated in Figure 5(a), the decreasing trend of annual UF is significant in 1980–1990 and 2000–2013 at the 0.05 significance level. UF and UB intersect in 2006 and break through the boundary line in 2012-2013. In autumn, UF and UB intersect in 1992 and break through the boundary line in 2005–2013, indicating a significant abrupt decrease in the trend. However, the trends in spring, summer, and winter are not significant. From the drought index, the only year with an annual severe drought is 2011. Years with severe or extreme droughts in the spring are 1987, 1988, 2010, and 2011. Years with severe or extreme droughts in the summer are 1972, 2011, and 2013. Years with severe or extreme droughts in the autumn are 1992 and 2009. Years with severe or extreme droughts in the winter are 1962 and 2009.

Figure 6 shows annual and seasonal trends in the RDI alongside an M-K test for Guizhou Province. The annual, spring, summer, autumn, and winter Z values were, respectively, −1.25, −1.24, −0.12, −2.34, and −0.98, and all showed a decreasing trend for autumn at the 0.05 significance level. The rate at which the trend decreases on annual and autumn timescales is larger, at −0.013/10a and −0.022/10a,

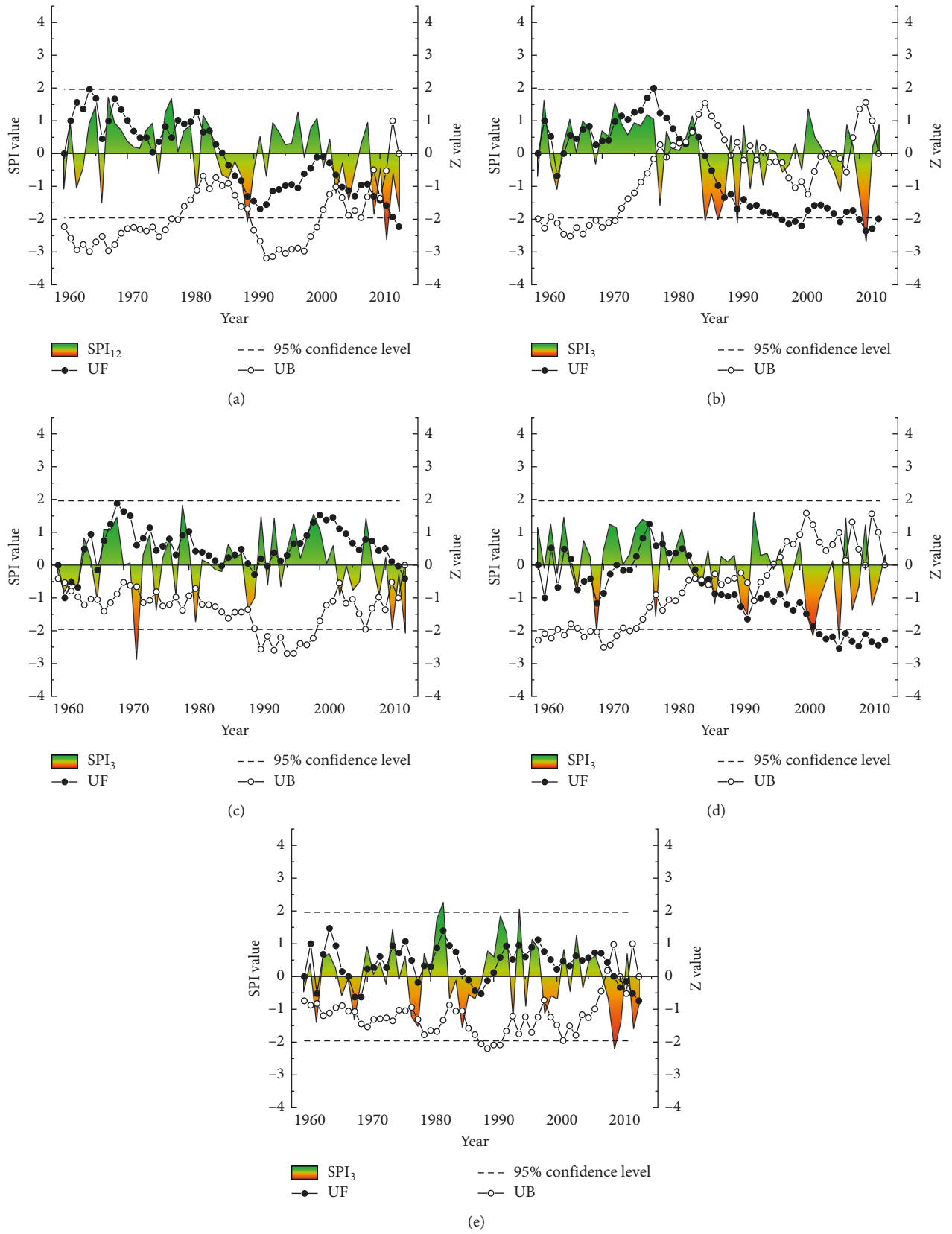

Figure 4: M-K trend test of the SPI (if the UF value > 0, the sequence shows a rising trend and indicating wet; UF value < 0 shows a falling trend and indicating drought): (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

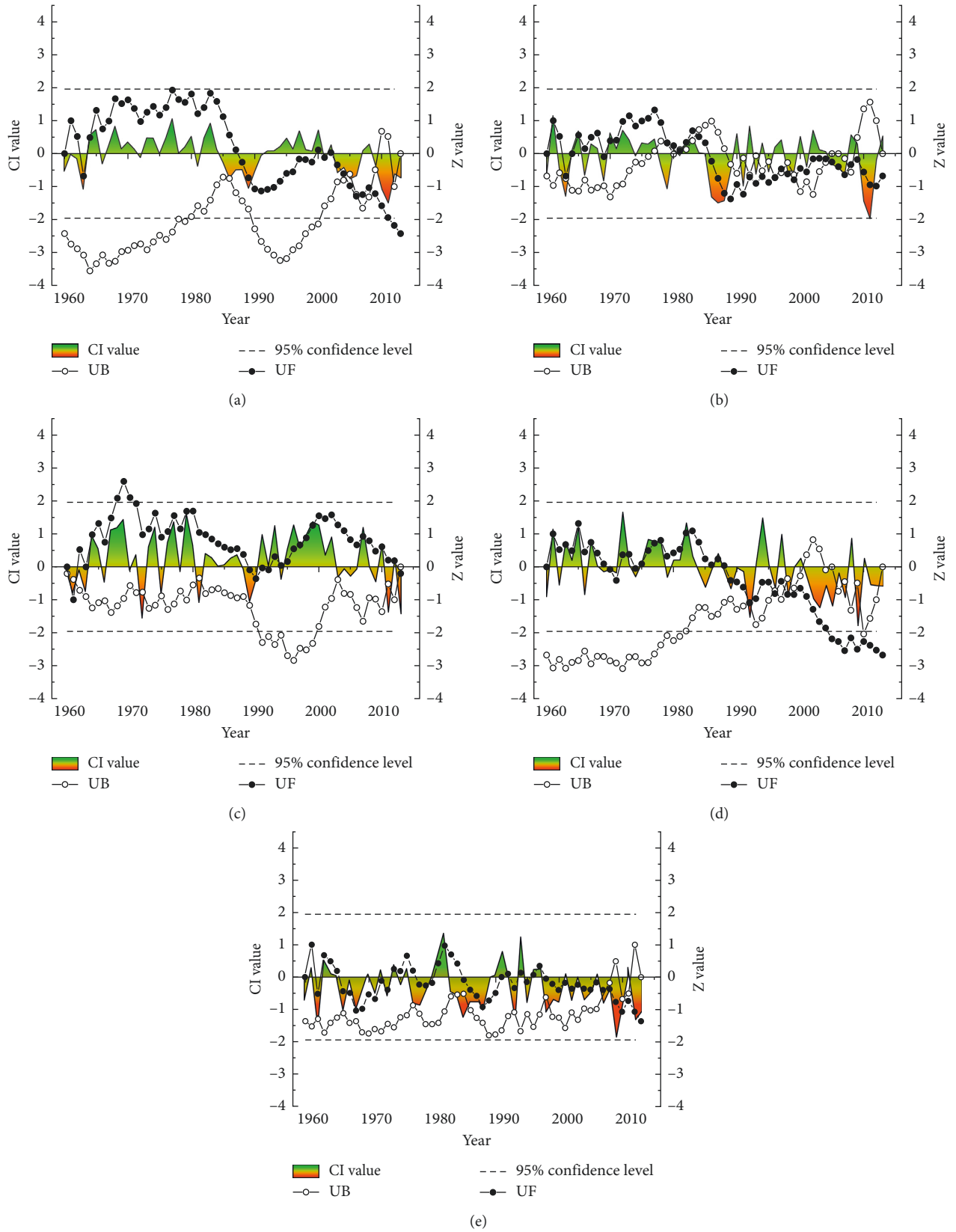

Figure 5: M-K trend test of the CI: (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

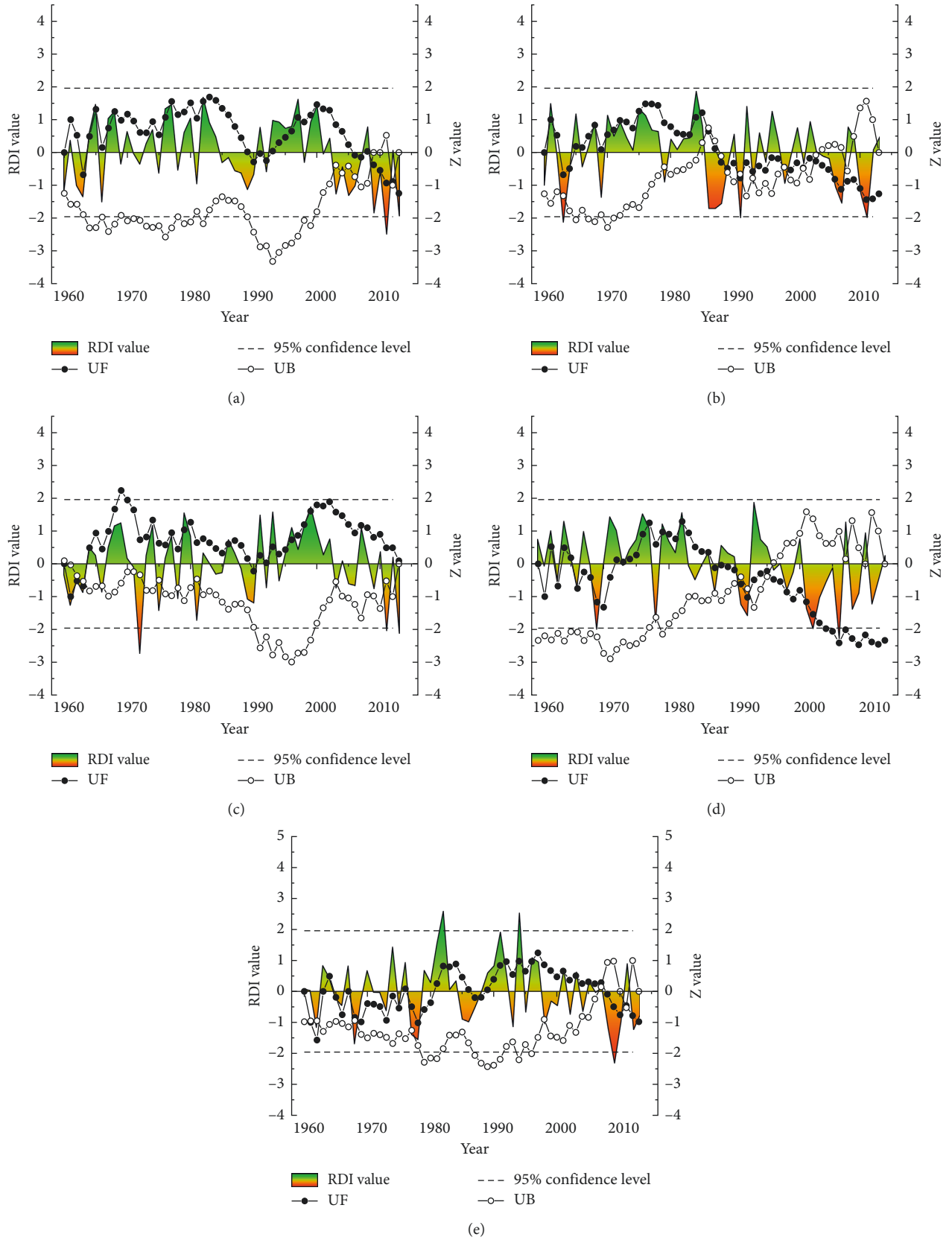

Figure 6: M-K trend test of the RDI: (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

Table 3: Identification of typical drought events by SPI, CI, and RDI in 1960–2013.

SPI			CI			RDI		
Event	Peak	Intensity	Event	Peak	Intensity	Event	Peak	Intensity
1960 (4-6/8-10)	**1960-1/8**	**3**	**1960 (1-4/8-12)**	**1960-1/10**	**5**	**1960 (4-6/8-12)**	**1960-4/8**	**5**
1963 (3-6/8-9)	**1963-6/8**	**5**	**1963 (3-6/8-9)**	**1963-6/8**	**4**	**1963 (3-6/8-9)**	**1963-6/8**	**7**
1966 (8-9)	**1966-9**	**3**	**1966 (1-4/8-9/11-12)**	**1966-3/9/11**	**4**	**1966 (8-9)**	**1966-9**	**2**
1966/1967 (11-1)	1967-1	2	1969 (2-5)	1969-2	3	1966/1967 (11-1)	1967-1	2
1969 (2-4)	1969-2	1	**1978 (2-4/7-9)**	**1978-2/7**	3	1969 (2-5/9-10)	1969-2/9	3
1978 (2-4/7-9)	**1978-2/7**	**2**	**1979 (1-5)**	**1979-3**	**3**	**1978 (2-4/7-9)**	**1978-2/7**	**3**
1978/1979 (12-5)	**1978-12**	**3**	**1979/1980 (11-1)**	**1979-11**	**2**	**1978/1979 (12-4)**	**1978-12**	**4**
1985/1986 (12-6)	**1986-5**	**4**	**1985/1986 (12-6)**	**1986-5**	**5**	**1985/1986 (10-6)**	**1986-5**	**4**
1987 (3-4)	**1987-3**	**2**	**1987 (3-5)**	**1987-3**	**2**	**1987/1988 (3-5/12-1)**	**1987-3/12**	**3**
1987/1988 (12-1/3-5)	**1987-12,1988-5**	**4**	**1988 (1-7/11-12)**	**1988-3/11**	**6**	**1988/1989 (3-7/11-1)**	**1988-5/11**	**4**
1988/1989 (11-1/5-8)	**1988-11,1989-5**	**2**	**1989 (5-12)**	**1989-11**	2	**1989 (7-8)**	**1989-8**	1
1992 (8-12)	**1992-8**	**3**	**1992/1993 (8-2)**	**1992-8**	**4**	**1992 (8-12)**	**1992-8**	**4**
1993/1994 (3-5/10-2)	1993-2/12	2	1995 (2-5)	1995-2	2	1993/1994 (3-6/12-2)	1993-3/12	2
1998 (9-12)	1998-9	1	1998/1999 (11-3)	1999-3	3	1998 (4-5/9-12)	1998-4/9	2
2002 (9-12)	2002-9	2	2002/2003 (11-3)	2002-11	2	2002 (9-12)	2002-9	2
2003 (8-11)	2003-8	2	2003/2004 (8-1)	2003-8	3	2003 (2-3/8-12)	2003-2/8	3
2005 (9-11)	2005-9	1	2005/2006 (9-1)	2005-9	3	2005 (9-12)	2005-9	1
2009/2010 (8-5)	**2010-2**	**7**	**2009/2010 (8-5)**	**2010-2**	**9**	**2009/2010 (8-5)**	**2010-2**	**7**
2011 (2-5/7-8)	**2011-4/7**	**6**	**2011 (2-5/7-9)**	**2011-4/7**	**7**	**2011 (4-5/7-9)**	**2011-4/7**	**5**
2013-2014 (1-2/7-8/10-2)	**2013-1/7/12**	**5**	**2012 (1-4/10-12)**	**2012-1/12**	**5**	**2013-2014 (1-2/6-8/10-2)**	**2013-1/7/12**	**6**
			2013/2014 (1-2/7-2)	**2013-1/7**	**6**			

Note. The bold values mean that they are consistent with the historical records.

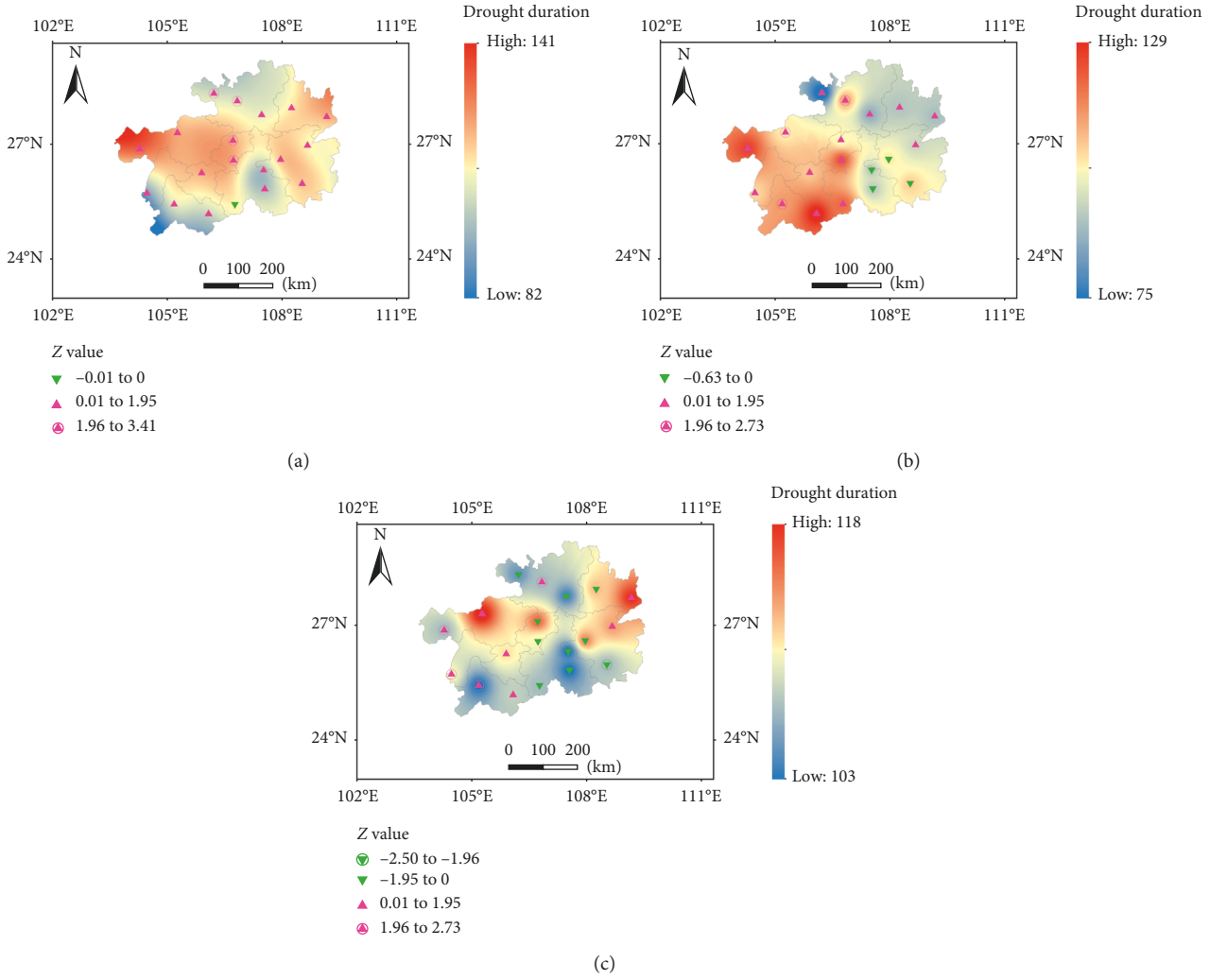

FIGURE 7: Trend distribution of drought duration: (a) SPI, (b) CI, and (c) RDI. The red dots indicate a significant positive trend ($Z > 1.96$) and the purple points indicate the insignificant positive trend ($0 < Z > 1.96$). The green points indicate the significant negative trend ($Z < -1.95$).

respectively. Figure 6(d) shows that UF and UB intersect in 1995 for autumn, breaking the boundary line in 2004–2013. However, the mutation in spring, summer, and winter was not significant. From the RDI, years with annual severe drought or extreme drought are 1966 and 2013, and 2009 and 2011, respectively. Years with severe or extreme droughts in the spring are 1986, 1987, 1988, 1991, and 2007, and 1963, 1991, and 2011, respectively. Years with severe or extreme droughts in the summer are 1981, and 1972, 2011, and 2013, respectively. Years with severe or extreme droughts in the autumn are 1978, 1992, and 1969, and 2002 and 2011, respectively. Years with severe or extreme droughts in the winter are 1968 and 1978, and 2009, respectively.

As shown in Table 3, 29, 30, and 32 drought events were identified from the SPI, CI, and RDI indices, respectively. The performances of the three indices are close with small differences on month scales. Identification of drought events in 1963, 1966, 1978-1979, 1985-1986, 1987-1988, 1988-1989, 1992, 2009-2010, 2011, and 2013-2014 is consistent for all three indices. We note that there were more droughts in the 1960s, 1980s, and 2000s, with a particular rise since the beginning of the 21st century. The drought peak also increased significantly since the beginning of the 21st century. Droughts classified as severe occurred in 1963, 1985-1986, 1987-1988, 1992, 2009-2010, 2011, and 2013-2014. In addition, as shown in Table 3, drought events took place in all seasons, especially in winter–spring and summer–autumn. There was a persistent drought in summer–autumn–winter–spring 2009-2010, a persistent drought in spring–summer 2011, and a persistent drought in winter–spring–summer–autumn 2013-2014.

4.2. Interannual Variability

4.2.1. Spatial Distribution and Trends of Drought Duration. The spatial distribution of drought durations and trends for the three indices is shown in Figure 7. Drought duration is longer in the northwest and relatively short in the southwest of Guizhou Province. In terms of the trend, only one station (Luodian station) shows a decreasing trend (i.e., a tendency to be wet). All other stations showed an increasing trend.

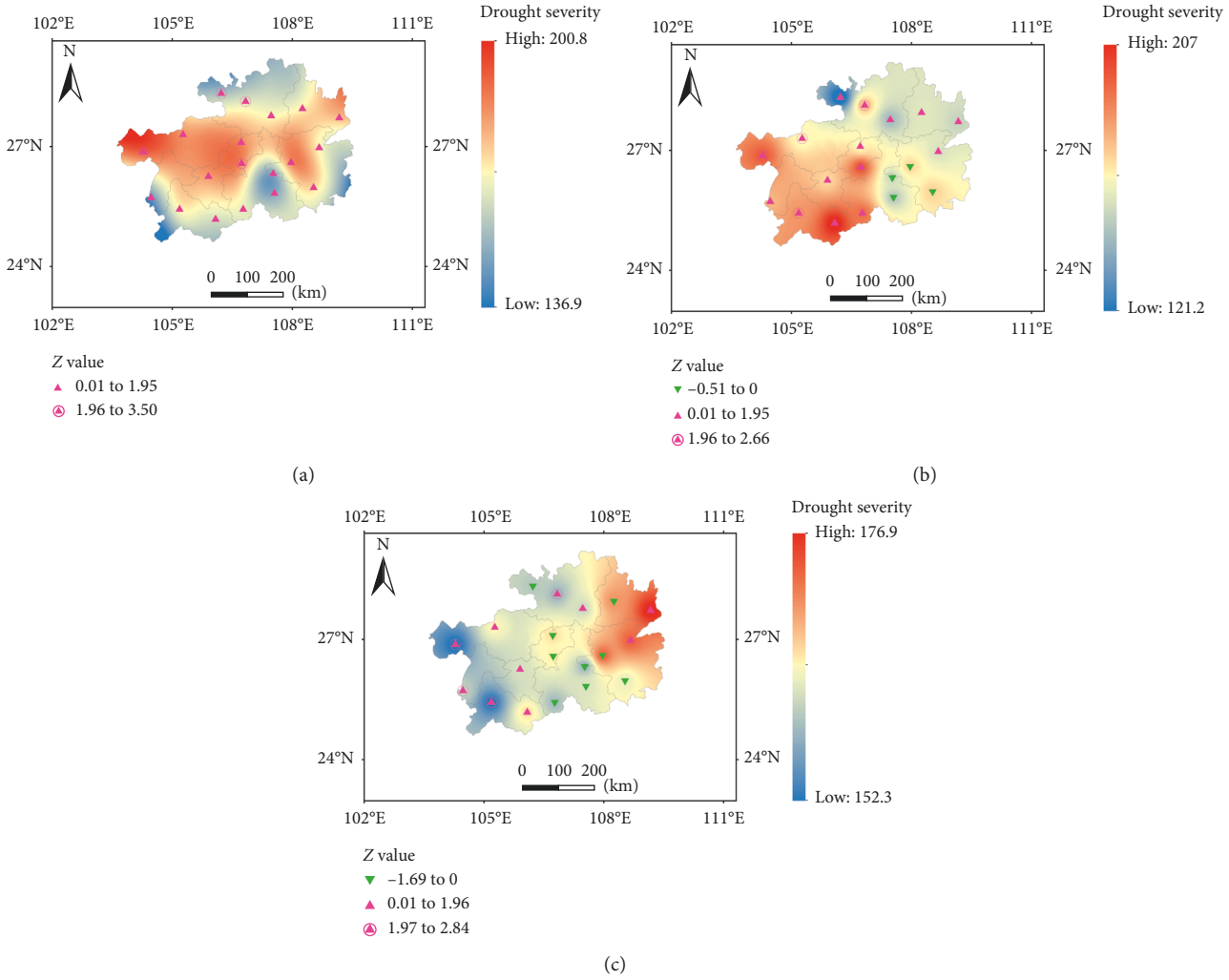

Figure 8: Trend distribution of drought severity: (a) SPI, (b) CI, and (c) RDI. The red dots indicate the significant positive trend ($Z > 1.96$) and the purple points indicate the insignificant positive trend ($0 < Z > 1.96$). The green points indicate the significant negative trend ($Z < -1.95$).

Among them, five stations (Weining, Guiyang, Xifeng, Xishui, and Tongzi stations) showed a significant increasing trend; these are mainly located in the northwest of Guizhou Province. The CI shows that droughts lasted for more and less time in western and northeast Guizhou Province, respectively. In terms of changes in the trend, four stations (Weining, Bijie, Tongzi, and Xingren stations) showed significant increasing trends; three of these stations are located in the west. Meanwhile, four stations (Kaili, Duyun, Dushan, and Rongjiang stations) showed non-significant decreasing trends in the southeast. The RDI suggests that drought duration is longer in northwest and northeast regions and shorter in southern Guizhou Province. Nine stations located in western Guizhou Province increased significantly. Furthermore, ten stations in central and eastern Guizhou Province had a decreasing trend. Among these was the one station in southeastern Guizhou (Rongjiang station) with a significant decreasing trend.

4.2.2. Spatial Distribution and Trends of Drought Severity. Figure 8 shows the spatial distribution and trends of drought severity. The spatial distribution of drought severity is almost consistent with that of drought duration. However, more severity droughts are typically found in the northwest of Guizhou Province, where all stations show an increasing trend. Stations with significant increasing trends are mainly distributed in the northwest and northeast of Guizhou Province. The drought severity determined by the CI is also consistent with drought duration. Drought intensity is of higher magnitude in western Guizhou Province. Among the four stations with significant increasing trends (Weining, Bijie, Panxian, and Tongzi stations), three (Weining, Bijie, and Panxian stations) are located in the west of the province, while drought duration showed a decreasing trend in southeast Guizhou Province. The drought intensity is also consistent with drought duration based on the RDI. Severe droughts are more frequent in eastern Guizhou. However, stations with significant increasing trends are primarily

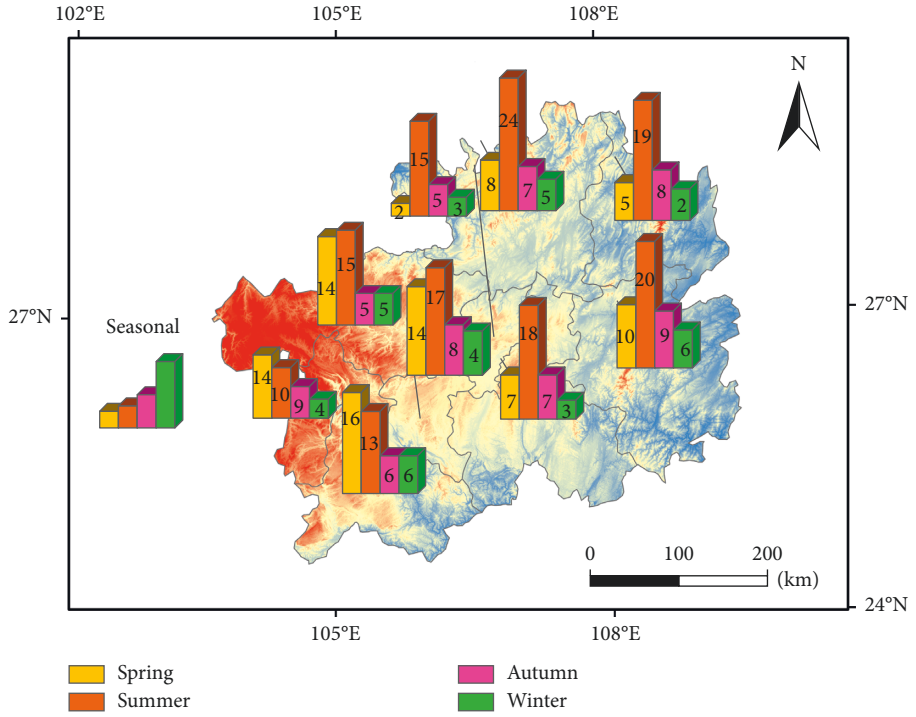

Figure 9: Statistics of seasonal drought frequency based on historical records in Guizhou Province in 1960–2013.

located in western Guizhou, while stations with both increasing and decreasing trends are located in northeast Guizhou, with stations with decreasing trends located in central and eastern Guizhou.

4.3. Validation of Three Drought Indices Based on Historical Disaster Records. Drought frequency in different seasons from 1960 to 2013 in Guizhou Province is shown in Figure 9, based on statistics of Chinese meteorological disasters [45–59]. More drought events are shown to have happened in spring and summer in Guizhou Province. Spring droughts are more frequent in the central and west of the Province, where Anshun City, Bijie City, and Qianxinan City are located. Summer droughts are more frequent in the central and east of Guizhou Province, home to Zunyi City, Tongren City, and Qiandongnan City. Moderate, severe, and extreme droughts are more frequent in spring in western Guizhou and summer in eastern Guizhou Province (Figure 10). Moderate and extreme droughts are more frequent in autumn and winter and mainly affect eastern Guizhou Province.

Figure 11 shows that droughts are more frequent in spring, summer, and autumn based on the SPI. However, droughts are less frequent in spring and summer than the historical records (Figure 9), while droughts in autumn are more frequent than the historical records. Winter droughts are highly consistent with historical records based on SPI. The CI suggests that drought occurrence increased in winter and spring. But the historical records show fewer droughts in winter. The CI is relatively close to historical records in spring, followed by autumn and summer. Autumn droughts occurred more frequently than the historical records. Fewer droughts in summer were found in the historical records. Drought predictions from the RDI are close to the historical records in spring and summer. However, this index suggests more droughts in autumn and winter, particularly in winter.

The mild and moderate seasonal droughts identified by the SPI are more frequent than those found in historical records. However, the severe and extreme seasonal droughts are identified less frequently than the historical records, especially in spring and summer (Figures 10 and 12).

The CI identifies more frequent mild and moderate seasonal droughts than the historical records, while it identifies fewer severe and extreme droughts than the historical record (Figures 10 and 13).

The RDI identifies more mild droughts than historical records indicate. However, the moderate, severe, and extreme droughts identified by the RDI are close to the historical records (Figures 10 and 14).

The drought frequency analysis (Figures 9 and 14) for SPI, CI, and RDI compared to the historical records shows that the mild and moderate droughts in winter are more than the historical records. The historical records describe the severity of the crop yield reduction. However, the drought indices do not take this into account. Thus, the drought statistics by indices are possible more frequently than the historical records. Overall, the severe and extreme droughts are less frequent than the historical records, especially CI. The RDI is closer to the historical records compared to the SPI and CI.

Figure 15 shows variation of the three drought indices in the area historically affected by droughts; among these data are the typical drought years shown in Table 4. The three drought indices in the drought-affected area were highest in 2011. However, the three drought indices in the affected area, particularly CI, are inconsistent with historical records in 2010, 1992, 1990, and 1988. Together with Figures 9–14,

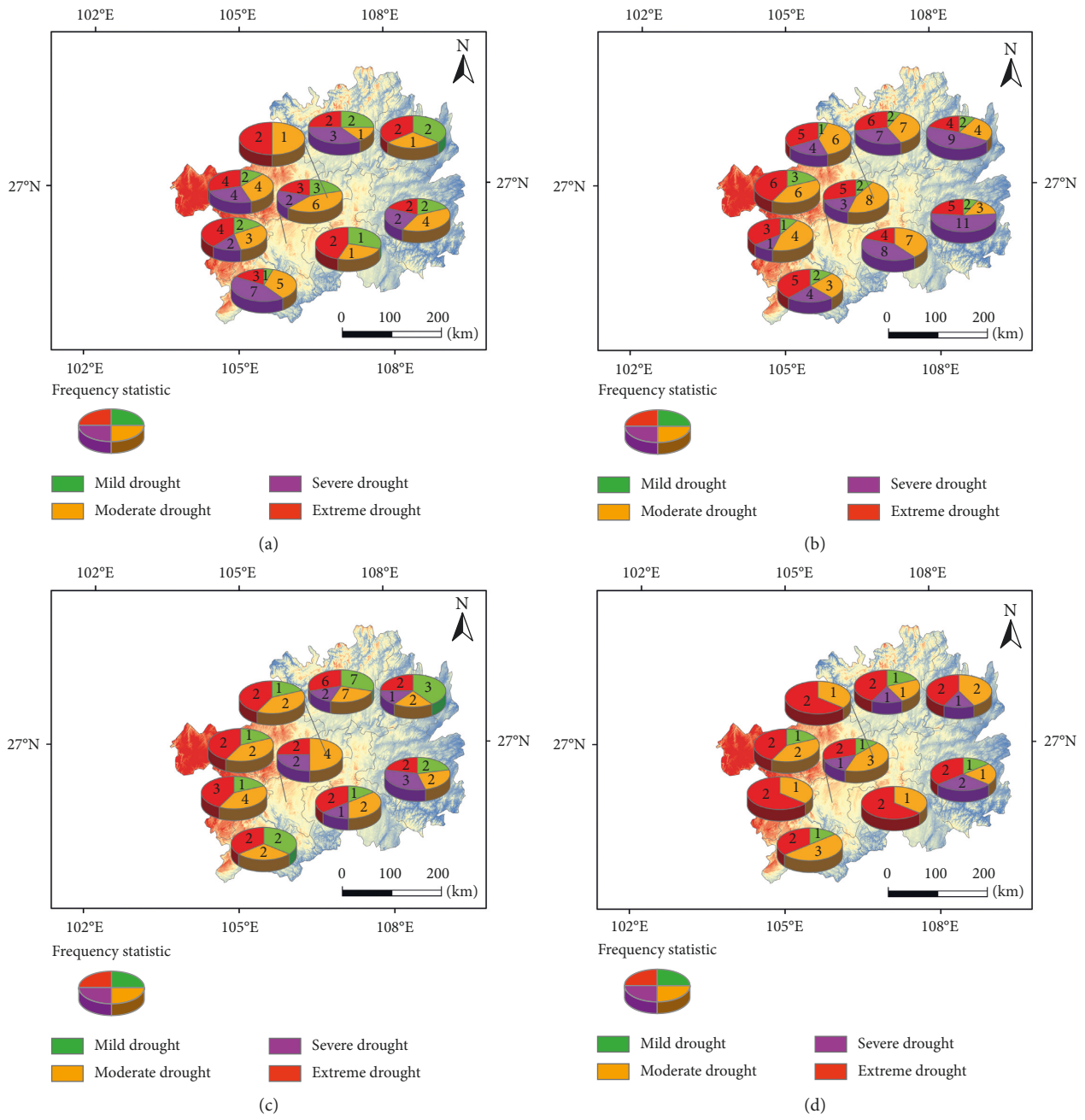

FIGURE 10: Statistics of seasonal drought frequency in different drought grades based on historical records in Guizhou Province in 1960–2013: (a) spring, (b) summer, (c) autumn, and (d) winter.

it is therefore shown that the RDI is more objective and reliable at indicating drought than the CI and SPI (the SPI_{12} value is shown here). Therefore, the abovementioned analysis indicated that the relationship between the historical records and drought index still needs to be further quantified in the future.

5. Discussion and Conclusions

All three drought indices showed decreasing trends in annual and seasonal in the past 54 years. The results are consistent with Zhai et al., Xu et al., Dai, and Milly and Dunne [8, 11, 60, 61]. However, Sheffield et al. [62] discovered that a little change in global drought for the period of 1948–2008 based on the Palmer drought severity index. Further, the presented results demonstrated a significant drought trend in autumn for the three drought indices, which are consistent with Li et al. [21] and Gao et al. [22]. These results also show that the drought in spring and summer are dominant from the historical records, which are increasing [43–51]. The autumn drought also shows a significant increasing trend in Guizhou Province, which may have a great impact on autumn crops. Gao et al. [22] found that autumn soil moisture anomaly is helpful to further

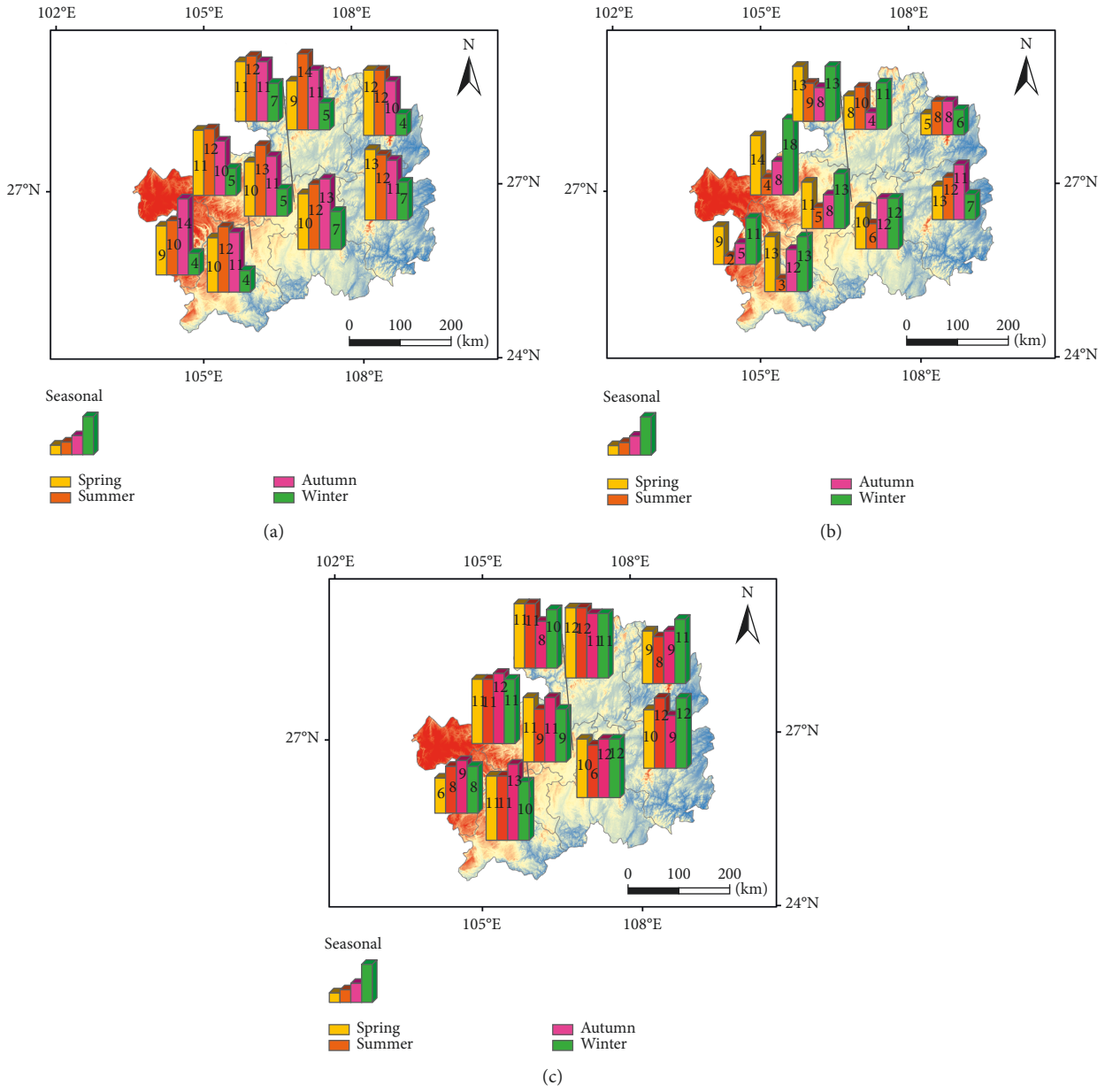

Figure 11: Statistics of seasonal drought frequency based on (a) SPI, (b) CI, and (c) RDI in Guizhou Province in 1960–2013.

understand the nature of the drought in Southwest China and may provide a clue for drought monitoring and risk management. The SPI, CI, and RDI identified 29, 30, and 32 drought events, respectively. Winter–spring and summer–autumn droughts have become more frequent since the beginning of the 21st century. The increase in frequency and strengthening trends of drought frequency, duration, peak, and intensity is significant over the period 1960–2013. These results are also consistent with Zhai et al., Yu et al., Xu et al., Li et al., and Gao et al. [8, 9, 11, 21, 22].

In terms of drought duration, the spatial distribution of the SPI is close with the RDI during 1960–2013. However, the spatial distribution of the CI is inconsistent with those of the SPI and RDI. As Section 3.1.2 mentioned that the CI index is composed of SPI and MI; however, some scholars point out that SPI and MI have certain defects. For instance, the SPI only utilizes precipitation information, without considering other meteorological variables that may play an important role for drought. In addition, the weight coefficients are relatively artificial and random, which may affect the ability of the CI [63–65]. Thus, it is possible to be the main reason for the disagreement with the distribution of RDI and SPI. For drought severity, the spatial distributions of the three drought indices are also inconsistent. In the present study, the drought severity is based on annual statistics. However, the seasonal statistics show that SPI and CI account for a large proportion in spring, while RDI accounts for a large proportion in summer. Therefore, SPI and CI show higher drought severity in the western province. The RDI shows higher drought severity in the eastern which is consistent with the historical records. Moreover, Xu et al. [11] also revealed that the spatial distribution of

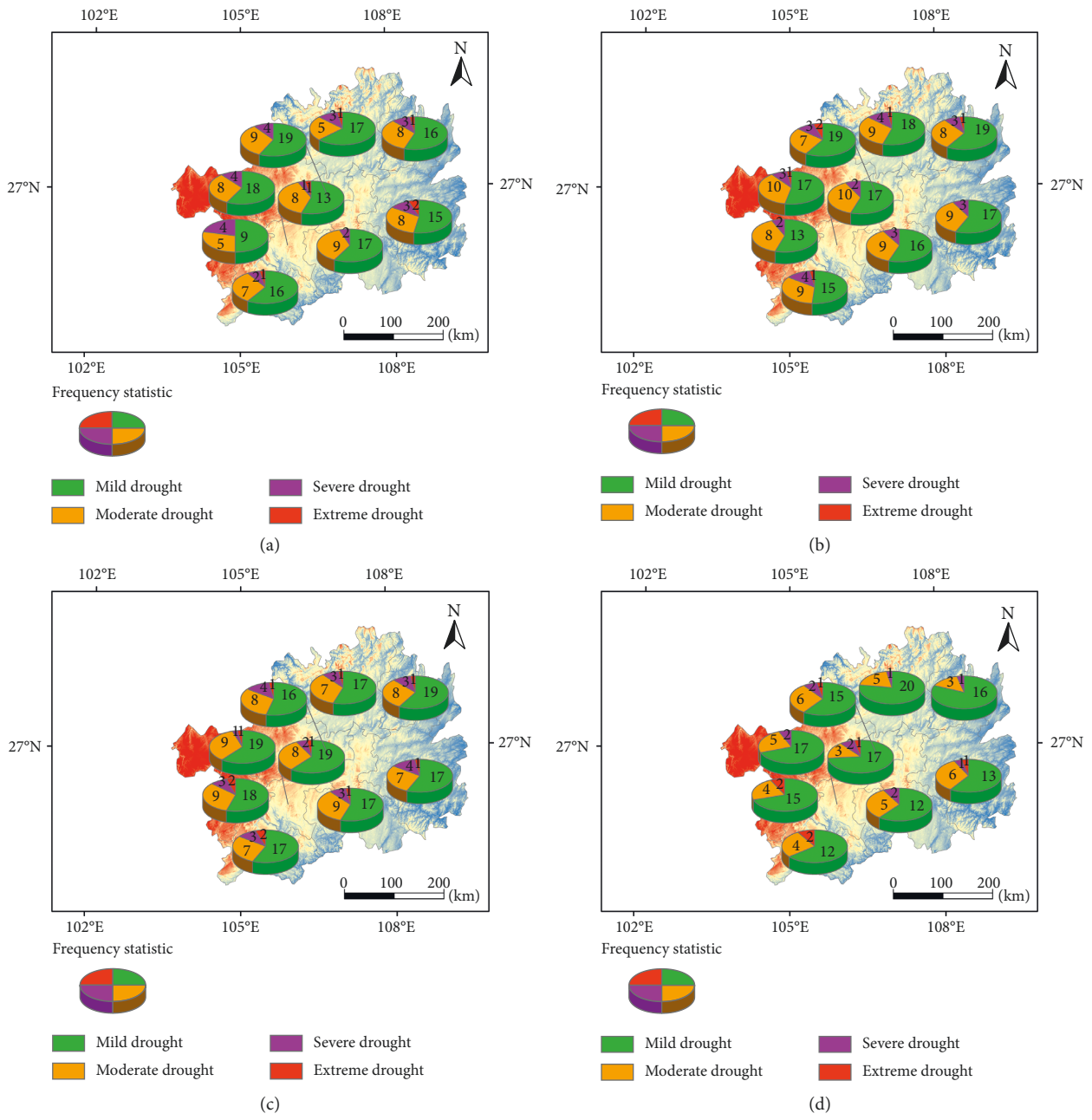

Figure 12: Statistics of seasonal drought frequency in different drought grades based on the SPI in Guizhou Province in 1960–2013: (a) spring, (b) summer, (c) autumn, and (d) winter.

drought severity using RDI_3 (3 months reconnaissance drought index) is almost the same as that using SPI_3 (3 months standardized precipitation index). However, the distributions of $SPEI_3$ (3 months standardized precipitation evapotranspiration index) are quite different with SPI_3 and RDI_3 as well as the trends. Based on the above analysis and the historical records (Table 3) of disasters in the drought-affected area that consider seasonal drought frequency and magnitude, the RDI performs more objectively and reliably than SPI and CI. However, the SPI, CI, and RDI all indicate drought frequencies and durations less or more than those indicated by the historical records. This may be related to the defects of the SPI, CI, and RDI. Previous studies have revealed that meteorological droughts are the water shortages caused by an imbalance precipitation and evaporation [66]. The most of the drought indices are mainly based on the precipitation and evaporation calculation. Therefore, they play a vital role in the capture of drought characteristics [11, 62]. Evaporation is always the focus of drought research. However, compared to precipitation, there are still many uncertainties in evaporation measurement. Therefore, different evaporation models may not get the same results. Previous studies applied PDSI, SPI, RDI, and SPEI [11, 60–62, 67], which mainly adopted the Thornthwaite and Penman–Monteith or other regimes to calculate the reference evapotranspiration (ETo). Therefore, different drought

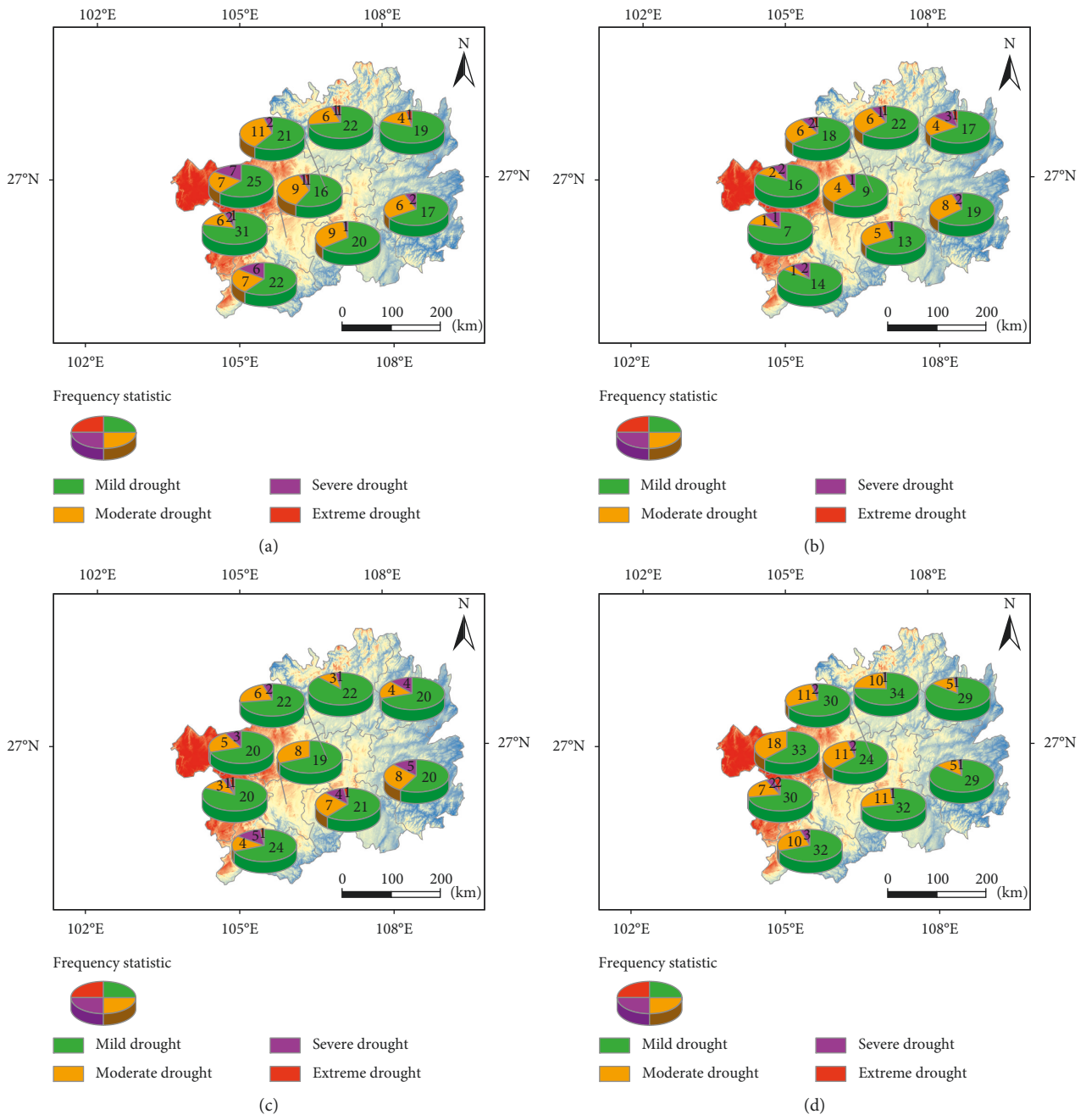

Figure 13: Statistics of seasonal drought frequency in different drought grades based on the CI in Guizhou Province in 1960–2013: (a) spring, (b) summer, (c) autumn, and (d) winter.

trends were obtained; for example, Dai [60] demonstrated that the observed global aridity changes are consistent with model predictions up to 2010, which suggest more severe and widespread droughts in the next 30–90 years caused by decreased precipitation or increased evaporation. Meanwhile, Milly and Dunne [61] also found that the historical and future tendencies are towards continental drying. However, Sheffield et al. [62] indicated that the previous reported increase in global drought is overestimated, and there was little change in drought over the period of 1948–2008. In addition, the results based on different drought indices are also inconsistent. For example, Zarch et al. [67] showed that the percentage of drought-prone areas estimated by the SPI is higher than that by the RDI for the period prior to 1998, while it is the converse for the period after 1998. Xu et al. [11] indicated that SPEI and RDI are sensitive to ETo. The RDI based on the Thornthwaite equation overestimates the influence of air temperature. Thus, it overestimates the grade of drought. Besides, Vicente-Serrano et al. [68] pointed out that SPI, PDSI, SPDI, and SPEI are sensitive to precipitation and ETo. The results may be quite different with respect to different indices.

All three drought indices indicate that mild droughts occurred more frequently than what is shown in the historical records, across different seasons and levels of

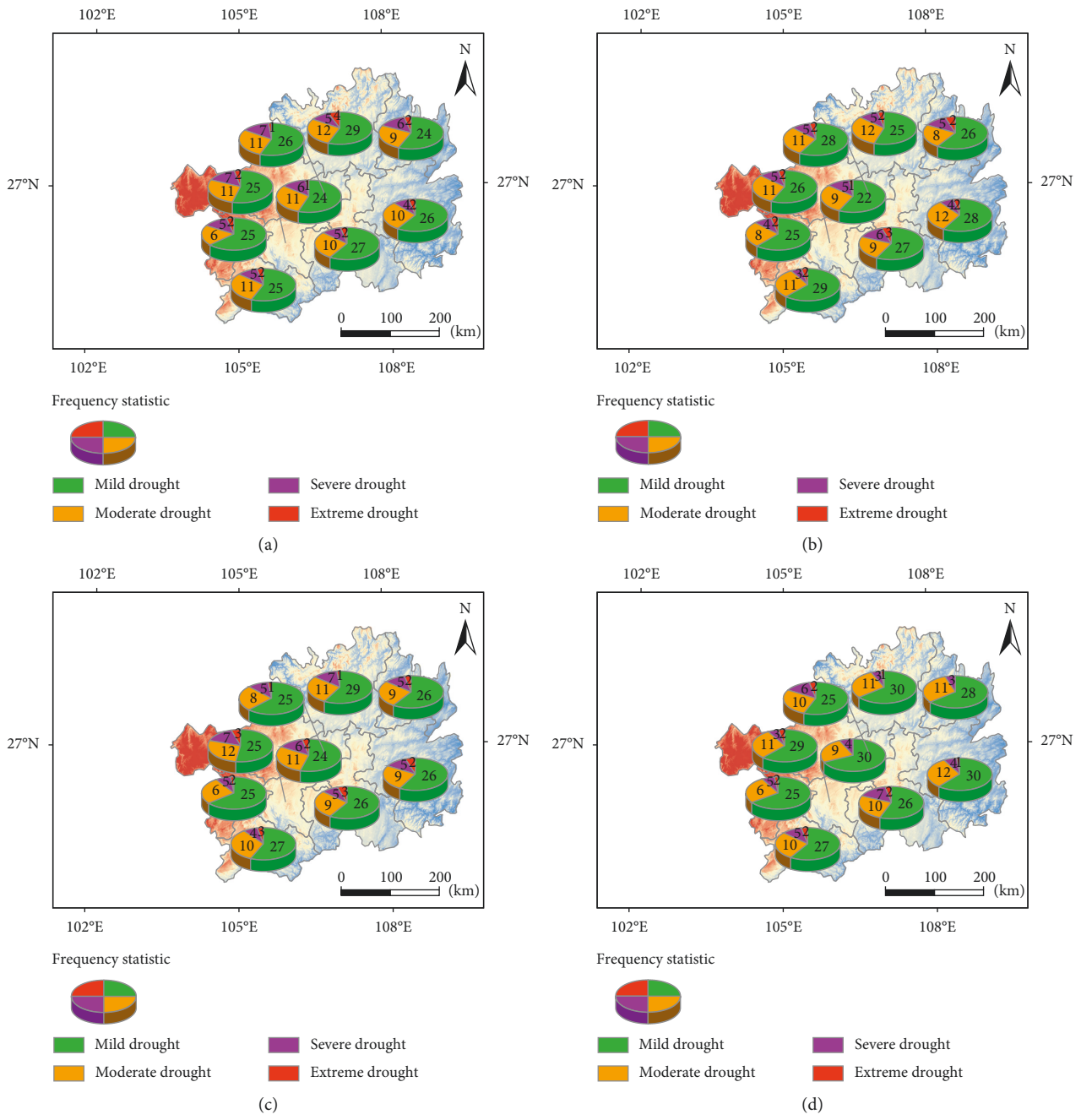

Figure 14: Statistics of seasonal drought frequency in different drought grades based on the RDI in Guizhou Province in 1960–2013: (a) spring, (b) summer, (c) autumn, and (d) winter.

drought. This may be related to different statistical analysis methods. In this paper, any interval when the indices are between −1 and 0 is classified as an occurrence of mild drought. However, it is necessary for a drought to cause agricultural and socioeconomic damage in order for it to be noted in historical records. We also point out that the drought-affected area was highest in 2011, consistent with RDI and CI, but not with SPI. The density of meteorological stations may also play a role. In this study, only data from 19 stations are considered. However, the records of drought-affected areas are based on statistics covering over 88 counties in the entire province. Thus, a higher density of weather stations may overcome the index-historical data mismatch.

Previous studies [69–73] have stated that the occurrence of droughts in the southwestern region of Guizhou Province is close to related atmospheric circulation anomalies and special topography [69–75]. In addition, the significant decrease in precipitation [11, 21] is an important factor for drought. Meanwhile, the change of potential evaporation is also a critical factor [20]. Chen et al. [41] pointed out that the number of continuous wet days (CWD) was decreasing

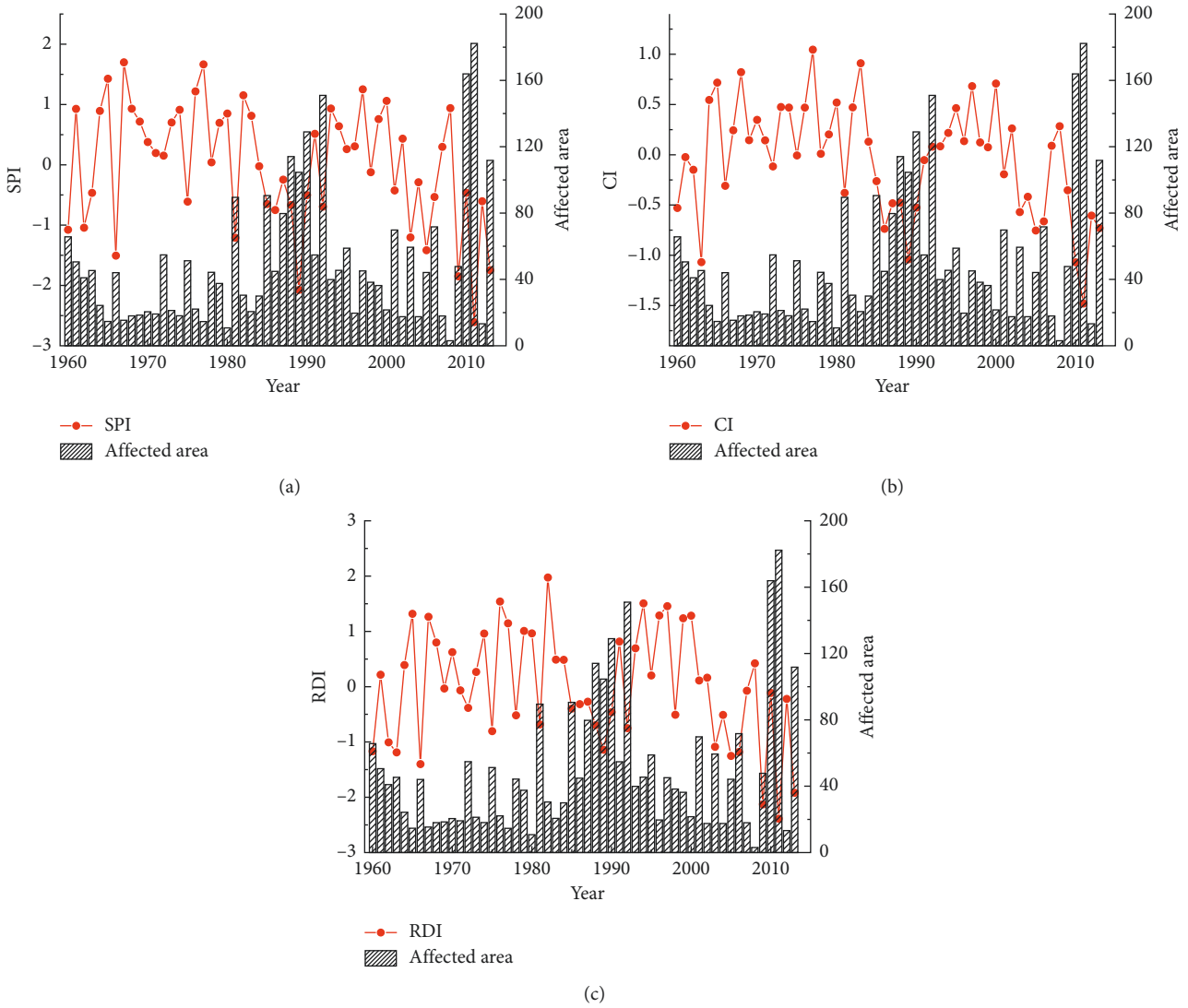

Figure 15: Comparison of drought-affected areas based on (a) SPI, (b) CI, and (c) RDI.

Table 4: Comparison of historical affected area in typical drought years based on the SPI, CI, and RDI.

Affected area ($\times 10^4$ hm^2)	1988	1989	1990	1992	2010	2011	2013
Historical	114.07	104.6	128.93	150.93	163.9	182.25	111.78
SPI historical	−0.7	−2.1	−0.5	−0.7	−0.5	−2.6	−1.7
CI historical	−0.5	−1.0	−0.5	−0.1	−1.1	−1.5	−0.7
RDI historical	−0.7	−1.1	−0.5	−0.7	−0.1	−2.4	−1.9

significantly while the largest 5 days of rainfall (RX5 day), strong precipitation (R95), and strongest rainy day (R20mm) measures did not have significant decreasing trends in response to the decreasing trend of the three indices (when considering Guizhou Province). In terms of drought distribution, all three drought indices indicated more frequent spring droughts in western Guizhou, and more frequent summer droughts in eastern Guizhou. Shen et al. [75] pointed out that drought characteristics are mainly the result of uneven spatiotemporal distribution of water resources in Guizhou Province. The spring drought is the most severe in Bijie City and Liupanshui City in western Guizhou Province. The rainy season in western Guizhou starts in June; when these rains are late, a spring drought is triggered. Zunyi, Tongren, and Qiannan Cities in eastern Guizhou Province are prone to summer droughts. This may be the result of the rainy season starting early (April) in the area. A precipitation decrease will likely cause a summer drought. Moreover, Milly and Dunne [61] and Sheffield et al. [62] stated that other factors such as runoff, relative humidity, wind speed, and other physical mechanisms should also be taken into account. The relationship between global drought and climate change can be assessed more accurately by combining physical hydrological models and large

quantities of measured and satellite remote-sensing data. Furthermore, the influence of human activities is also an important factor that cannot be ignored.

The karst landform is also an important factor for the drought in Guizhou Province [72]. The karst topography is widely distributed in Guizhou Province, and the arable land is mainly located in the high mountains [73, 74]. However, the water source for irrigation is located at the bottom of the valley. Due to the widespread karst, the soil layer is infertile with a poor water storage capacity. Further, water permeability is strong, and water moves quickly through the rocks. Therefore, in such a region, once drought occurs, it will have an important impact on agricultural production and domestic water. The historical records indicate that spring and summer droughts have begun to occur more frequently in Guizhou Province. Based on analysis of the three indices considered in this paper, the annual and seasonal drought trends, especially for autumn droughts, are more significant. These results demonstrate that the government of Guizhou Province should focus on monitoring and damage prevention not only for the spring and summer droughts but also for the autumn drought.

In this study, three indices are used to describe the spatiotemporal characteristics of Guizhou Province during 1960–2013. The comparison analysis shows that the RDI is much closer to the historical records than CI and SPI. The RDI may be more reliable for drought monitoring in this region. However, this study is limited in some aspects. The historical records are more often qualitative descriptions. When we extracted the drought information, the disaster loss (such as crop loss), duration, and other information were comprehensively considered. However, the drought index is a quantitative indicator that is more sensitive to weather conditions. It does not identify the crop loss information. Thus, the drought index tends to identify more mild droughts. Definitely, it is a great challenge to match the qualitative description for the quantitative indicator. However, we believe that this study still can provide a useful reference for drought monitoring and assessment. This issue will be further improved in the future work. In addition, the atmosphere or other meteorological variables are not investigated. The mechanisms responsible for the drought in Guizhou Province need to be further explored. Improving and modifying the drought index is also the topic of ongoing work and future research.

Conflicts of Interest

The authors declare that there are no conflicts of interest in this paper.

Acknowledgments

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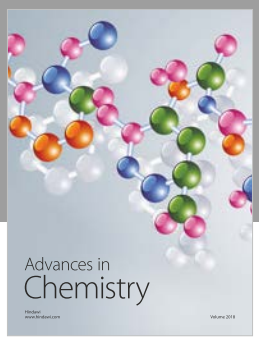

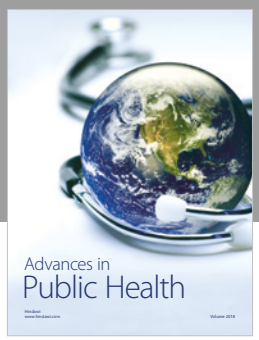

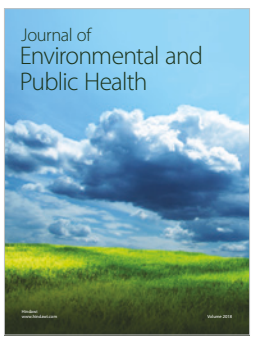

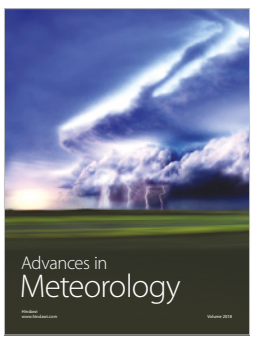

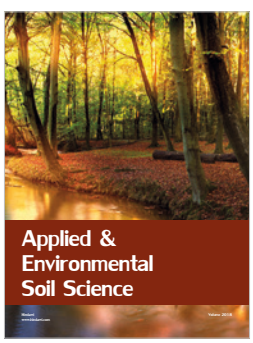

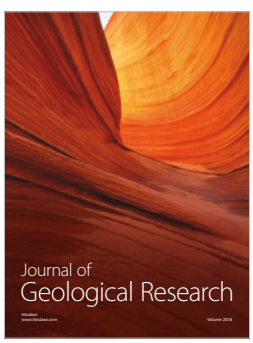

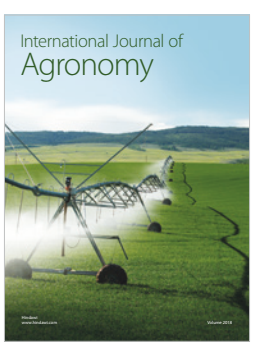

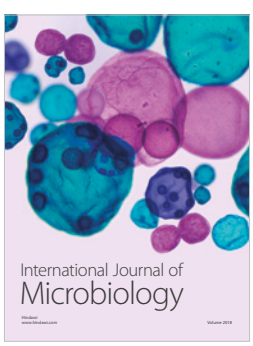

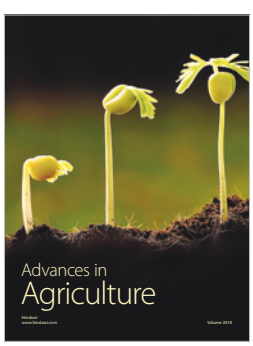

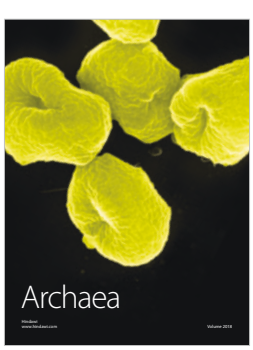

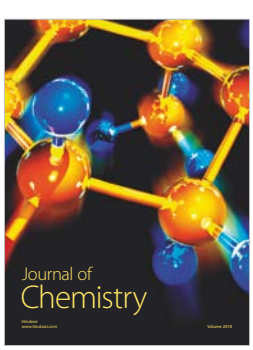

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