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Spatial–temporal variations of spring drought based on spring-composite index values for the Songnen Plain, Northeast China

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Abstract A spring-composite index (s-CI) is proposed in this study that involves slightly altering the use of the accumulated precipitation from the composite index (CI) comparing the value with other three commonly used indices (standardized precipitation index, SPI; self-calibrated Palmer drought severity index, sc-PDSI; and CI). In addition, the spatial–temporal variation of the s-CI in the Songnen Plain (SNP) was investigated using the Mann–Kendall test and empirical orthogonal function (EOF) methods. The results indicated that the proposed s-CI could identify most drought events in 1990s and 2000s and performed relatively better than SPI, sc-PDSI, and CI in this region. Compared with the other three indices, the s-CI had a higher correlation with relative soil moisture in April and May. The recent spring droughts (2000s) were the most severe in April or May. The weather was drier in May compared with April in the 1980s, whereas the weather was wetter in May than in April in the 1960s and 1970s. Moreover, the spatial patterns of the first EOFs for both April and May indicated an obviously east–west gradient in the SNP, whereas the second EOFs displayed north–south drought patterns. The proposed index is particularly suitable for detecting, monitoring, and exploring spring droughts in the Songnen Plain under global warming.

1 Introduction

Intense drought can cause severe damage to agriculture, the economy, and the environment (Wilhite 1993). However, drought characteristics are always difficult to quantify due to the complexities of measuring intensity, magnitude, duration, and spatial extent (Vicente-Serrano et al. 2010). For these reasons, much effort has been expended to develop techniques for drought monitoring and analysis. Among these techniques, drought indices are the most important and commonly used tools for drought evaluation because they simplify the complex interrelationships between many climate and climate-related parameters.

During the last century, a number of indices were proposed and modified (Heim 2002; Keyantash and Dracup 2004; Tsakiris et al. 2007). Some indices, such as the standardized precipitation index (SPI), the Palmer drought severity index (PDSI), and the composite index (CI), are widely used in drought monitoring and analysis. The SPI was initially proposed for drought monitoring in Colorado and can be used to express different drought types at multi-scale (McKee et al. 1993). Short time scales (months or weeks) may be important in agricultural water management, whereas longer time scales (1 year or even longer) are more connected to water supply management. The PDSI is a landmark in the development of drought indices (Vicente-Serrano et al. 2010). The index enables the measurement of dryness (negative values) and

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wetness (positive value) based on the supply and demand concept of the water balance equation, and thus, the PDSI incorporates prior precipitation, moisture supply, runoff, and evapotranspiration demand at the surface (Palmer and Bureau 1965). The CI is provided by the National Climate Center of China and is used for provincial meteorological monitoring (Liu et al. 2009; Li et al. 2009; Qian et al. 2011). It is based on a combination of meteorological variables such as precipitation and evapotranspiration. In addition, short time scales (1 month) and multi-scale SPI (3 months) are used in the CI.

Certainly, no single index has been able to adequately capture the intensity and severity of all different droughts in different regions because of the complexity of drought (Heim 2002). Therefore, it is hard to claim that one drought index is better than another, and it is better to select a suitable index after taking into consideration the needs of the different regions and users. The Songnen Plain (SNP) is one of the most important agricultural areas in Northeast China as stated by the "Plan for Increasing the National Grain Production Capacity by 50 Billion Kilograms (2009–2020)" (Zhang 2004; Liang et al. 2011). Unfortunately, during the past 50 years, the region has suffered huge economic losses due to frequent long-duration spring droughts that affected large areas (Xi et al. 2008; Li et al. 2006; Xie et al. 2003; Bai et al. 2004). A few studies related to spring drought in the Songnen Plain have been conducted using the SPI, PDSI, and CI (Zhai et al. 2010; Qian et al. 2011). However, these indices always have their inherent drawbacks. For example, the SPI is solely based on precipitation and does not account for other factors (e.g., evapotranspiration) that also have important influences on drought (Vicente-Serrano et al. 2010). Although the PDSI represents surface moisture conditions better than precipitation alone, the index cannot reasonably represent the soil moisture conditions of Northeast China during the winter and spring months (Dai et al. 2004). The CI can standardize drought condition at different time scales, which allows a comparison of drought events at different stations (Qian et al. 2011). The CI in spring takes the accumulated precipitation of the previous winter or the current spring as the antecedent conditions. However, there are still some drawbacks in the existing spring CI. Shen et al. (1980) indicated that the formation and occurrence of spring drought in Northeast China is related to both the spring precipitation and also to soil water storage of the previous autumn before soil is frozen (Shen et al. 1980). Using a field experiment, Sun and Bai (2005) also found that the spring soil moisture is considerably related to the accumulated precipitation of the previous autumn in the SNP (Sun and Bai 2005). Therefore, in this study, we propose a spring composite index (s-CI) that is a slight alteration of the popularly used CI. Our proposed index takes into account the previous autumn precipitation as an antecedent condition affecting spring drought.

The main objectives of this study were the following: (1) to propose a spring drought index (s-CI) that is a slight alteration of the popularly used CI, (2) to compare the s-CI with three other commonly used drought indices (SPI, sc-PDSI, and CI) for spring drought investigation of the SNP, and (3) to investigate the spatio-temporal variations of spring drought based on the suitable index for the SNP.

2 Materials and methods

2.1 Study area

The Songnen Plain (SNP, 121°20′–128°25′ E and 43°36′–49° 30′ N) is located in the central part of Northeast China, with the Changbai Mountain forming a boundary to the east, Daxing'an Mountain forming a boundary to the west, and Xiaoxing'an Mountain forming a boundary to the north. The SNP covers an area of approximately 1.8×10^5 km^2, including southwestern Heilongjiang province and western Jilin province (Fig. 1). The main cities in this area are Harbin, Qiqihaer, and Baicheng.

Geographically, the SNP consists of a piedmont area in the west, a central low plain, and an elevated plain in the east. Most of the plain is less than 200 m above sea level. The climate is continental to semi-arid. As a result of the large topographic elevation differences and the surrounding mountains, the precipitation varies widely. The mean annual precipitation ranges from 500–600 mm in the east elevated plain to 300–450 mm in the west piedmont area (Chen et al. 2011). As controlled by the East Asian monsoon, the precipitation in the SNP area changes dramatically during an annual cycle but is mainly concentrated around the flood season (June to September) (Wang and Ripley 1997), and only 10–20 % of this precipitation falls in spring (Li et al. 2006). The mean annual temperature ranges from −4 to +10 °C and gradually decreases from south to north. Pan evaporation is between 700 and 1,000 mm, more than 40 % of which is spring evaporation (Zhang et al. 2011). Seasonal drought is frequent in the spring and autumn, and 90 % of springs experience drought (Liu et al. 2011). The droughts with long duration and large areas cause great losses to agricultural production and the economy (Bai et al. 2004).

2.2 Data description

In the SNP, the near-surface is almost covered by permafrost in March, and the arable layer begins to melt starting from April. Consequently, this study focused only on spring drought in April and May, which are critical agricultural months in the SNP.

2.2.1 Meteorological data

The precipitation, maximum air temperature, minimum air temperature, relative humidity, sunshine hours, and wind

Fig. 1 Location of the Songnen Plain in China and its stations

speed datasets covering 31 stations within and around the SNP (Fig. 1) were provided by the China Meteorological Administration (CMA), which is in charge of monitoring, collecting, compiling, and releasing hydro-meteorological data in China (Zhao et al. 2012). These stations are maintained according to standard methods of the World Meteorological Organization's guide to the Global Observing System and the CMA's Technical Regulations on Weather Observations (Fu et al. 2013). The data were quality-controlled and their consistencies were tested before being released by the CMA (http://cdc.cma.gov.cn). In this study, there was no missing data in the monthly meteorological dataset from 1958 to 2010. The climate variables covered a 53-year (1958–2010) period, but only 52-year subsets (1959–2010) were used due to the calculation of s-CI being based on the precipitation of the previous autumn.

2.2.2 Drought records and relative soil moisture

The spring drought records of the five stations (Nenjiang, Fuyu, Baicheng, Changling, and Harbin) in the SNP (Fig. 1) were provided by the CMA. The drought data from the drought-monitor stations included afflicted crops, occurrence time, severity, durations, afflicted areas, and ratios (Tables 1 and 2). The drought magnitude in this dataset is one kind of drought-

category index by percentage of afflicted crops according to the standards of agro-meteorological observation (CMA 1993). The drought records (April and May) covered 19 years (1992–2010).

The crop growth relative soil moisture data was recorded and maintained by the CMA (Huang and Li 2010). The dataset contains data on crops, growth periods, heights of crops, the conditions of growth, density of crops, and relative soil moisture for the 10-, 20-, 50-, 70-, and 100-cm layers. Three stations (Nenjiang, Baicheng, and Changling) for the April data and five stations (Nenjiang, Fuyu, Baicheng, Changling, and Harbin) for the May data (Fig. 1) were used for comparing drought indices with spring relative soil moisture in the SNP. The relative soil moisture data of the 10- and 20-cm layers of April and the relative soil moisture data of the 10-, 20-, 50-, and 70-cm (only Fuyu station) layers of May were used in this study. The length of the observed relative soil moisture period (April and May) was 19 years (1992–2010). However, there were indeed some missing data for soil layers of different stations. The years with missing data were simply removed, which leads to the sample size of 7–19 for different soil layers with an average of 16. The spring drought records data and the relative soil moisture data were compiled after manual review by the CMA (http://cdc.cma.gov.cn).

Table 1 Meteorological stations used in this study

Station	Latitude (N)	Longitude (E)	Elevation (m)	Data series	Data type	Length of observations[a]
Nenjiang	125.23	49.17	242.2	P, T, RH, SH, W	Monthly	1959–2010
Sunwu	127.35	49.43	234.5	P, T, RH, SH, W	Monthly	1959–2010
Xiaoergou	123.72	49.2	286.1	P, T, RH, SH, W	Monthly	1959–2010
Beian	126.52	48.28	269.7	P, T, RH, SH, W	Monthly	1959–2010
Keshan	125.88	48.05	234.6	P, T, RH, SH, W	Monthly	1959–2010
Yichun	128.92	47.73	240.9	P, T, RH, SH, W	Monthly	1959–2010
Zhalantun	122.73	48.00	306.5	P, T, RH, SH, W	Monthly	1959–2010
Fuyu	124.48	47.80	162.7	P, T, RH, SH, W	Monthly	1959–2010
Qiqihaer	123.92	47.38	147.1	P, T, RH, SH, W	Monthly	1959–2010
Hailun	126.97	47.43	239.2	P, T, RH, SH, W	Monthly	1959–2010
Mingshui	125.90	47.17	247.2	P, T, RH, SH, W	Monthly	1959–2010
Tieli	128.02	46.98	210.5	P, T, RH, SH, W	Monthly	1959–2010
Suihua	126.97	46.62	179.6	P, T, RH, SH, W	Monthly	1959–2010
Anda	125.32	46.38	149.3	P, T, RH, SH, W	Monthly	1959–2010
Tailai	123.42	46.40	149.5	P, T, RH, SH, W	Monthly	1959–2010
Tonghe	128.73	45.97	108.6	P, T, RH, SH, W	Monthly	1959–2010
Wulanhaote	122.05	46.08	274.7	P, T, RH, SH, W	Monthly	1959–2010
Harbin	126.77	45.75	142.3	P, T, RH, SH, W	Monthly	1959–2010
Shangzhi	127.97	45.22	189.7	P, T, RH, SH, W	Monthly	1959–2010
Baicheng	122.83	45.63	155.3	P, T, RH, SH, W	Monthly	1959–2010
Qianan	124.02	45.00	146.3	P, T, RH, SH, W	Monthly	1959–2010
Qianguo	124.87	45.08	136.2	P, T, RH, SH, W	Monthly	1959–2010
Sanchahe	126.00	44.97	196.8	P, T, RH, SH, W	Monthly	1959–2010
Tongyu	123.07	44.78	149.5	P, T, RH, SH, W	Monthly	1959–2010
Changling	123.97	44.25	188.9	P, T, RH, SH, W	Monthly	1959–2010
Zhaluteqi	120.90	44.57	265.0	P, T, RH, SH, W	Monthly	1959–2010
Changchun	125.22	43.90	236.8	P, T, RH, SH, W	Monthly	1959–2010
Jiaohe	127.33	43.70	295.0	P, T, RH, SH, W	Monthly	1959–2010
Tongliao	122.27	43.60	178.7	P, T, RH, SH, W	Monthly	1959–2010
Shuangliao	123.53	43.50	114.9	P, T, RH, SH, W	Monthly	1959–2010
Siping	124.33	43.17	165.7	P, T, RH, SH, W	Monthly	1959–2010

In the data series column, P, T, RH, SH, and W indicate precipitation, temperature (maximum air temperature, minimum air temperature), relative humidity, sunshine hours, and wind speed, respectively

[a] The T, RH, SH, and W series data was from 1959–2010. To calculate the previous autumn SPI3, the length of the P series used was 1958–2010.

Table 2 Disaster stations used in this study

Station	Latitude (N)	Longitude (E)	Elevation (m)	Data series	Data type	Length of observations
Nenjiang	125.23	49.17	242.2	SDR, RSM4, and RSM5	Monthly	1992–2010
Fuyu	124.48	47.80	162.7	SDR and RSM5	Monthly	1992–2010
Harbin	126.77	45.75	142.3	SDR and RSM5	Monthly	1992–2010
Baicheng	122.83	45.63	155.3	SDR, RSM4 and RSM5	Monthly	1992–2010
Changling	123.97	44.25	188.9	SDR, RSM4, and RSM5	Monthly	1992–2010

In the data series column, SDR, RSH4, and RSH5 indicate the spring drought records, relative soil moisture of April, and relative soil moisture of May, respectively

2.2.3 The standardized precipitation index (SPI)

The standardized precipitation index, which was constructed based on a precipitation probabilistic approach, was initially proposed for drought monitoring in Colorado (McKee et al. 1993). It has been widely used to express different drought types using multi-scales and in different regions (Zhai et al. 2010; Liu et al. 2012b; Wang et al. 2011; Potop et al. 2012; Kim et al. 2011; Bonaccorso et al. 2003; Li et al. 2011). The SPI1 represents the present lack of precipitation, whereas the SPI3 represents the accumulated lack of precipitation. In this study, the 1-month SPI1 (SPI1_4 for April and SPI1_5 for May) of 1992–2010 and 1959–2010 and the 3-month SPI3 (SPI3_4 for April, SPI3_5 for May, and SPI3_{11} for November) of 1958–2010 at 31 weather stations were calculated. More details can be found at http://ccc.atmos.colostate.edu/pub/spi.pdf. Furthermore, the SPI calculation procedure can be downloaded from http://drought.unl.edu/monitor/spi/program/spi_program.htm.

2.2.4 The self-calibrated Palmer drought severity index (sc-PDSI)

The PDSI is widely used for representing the severity of dry or wet conditions and is based on temperature, precipitation, and soil moisture conditions (Palmer and Bureau 1965). To improve the spatial comparability, one may use "the self-calibrated PDSI," which is re-calibrated to local conditions and appears to be a superior drought index (Dai 2011). In this study, the gridded sc-PDSI values of five stations (Nenjiang, Fuyu, Baicheng, Changling, and Harbin) for spring 1992–2010 as determined based on the Penman–Monteith methods were downloaded from http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html.

2.2.5 The composite index

The composite index (CI), which was constructed based on the SPI at multi-scales, relative moisture index (M), and the precipitation amount, is commonly used for regional meteorological monitoring (Li et al. 2009; Qian et al. 2011; Liu et al. 2009). It was calculated using the method of Zou and Zhang (2008):

$$CI = a \times SPI1 + b \times SPI3 + c \times M \tag{1}$$

where SPI1 was the SPI calculated using the 1-month recent precipitation (SPI1_4, SPI1_5) and SPI3 was the SPI calculated using precipitation for 3-month recent precipitation (SPI3_4, SP3_5). M was the relative moisture index and was calculated as follows:

$$M = (P{-}E)\big/ E \tag{2}$$

where P was precipitation and E was potential evapotranspiration. The Penman–Monteith (PM) equation was used to calculate the E in spring. The parameters a, b, and c in Eq. (1) were taken as 0.4, 0.4, and 0.8, respectively (Zou and Zhang 2008). In this study, the CIs of five stations (Nenjiang, Fuyu, Baicheng, Changling, and Harbin) for the spring of 1992–2010 were calculated by Eq. (1).

2.2.6 The spring composite index (s-CI)

In the spring of SNP, the snow remaining on the soil surface quickly melts and even directly transforms into atmospheric vapor. Therefore, this snow has a limited effect on the soil moisture. Precipitation in the previous autumn is the main antecedent factors affecting the spring drought (Sun and Bai 2005). Based on the formulation of CI, the s-CI was calculated as follows:

$$s - CI = a \times SPI1 + b \times SPI3' + c \times M \tag{3}$$

where SPI1 was the SPI value constructed using the precipitation of April and May (SPI1_4, SPI1_5) and SPI3′ was the SPI constructed using the precipitation of the previous September–November (SPI3_{11}). M was the relative moisture index of April or May, which can be calculated from the formulation (2). The parameters a, b, and c were also taken as 0.4, 0.4, and 0.8, respectively. In this study, the s-CI values of five stations (Nenjiang, Fuyu, Baicheng, Changling, and Harbin) for the spring of 1992–2010 and the s-CI values of 31 stations of 1959–2010 were calculated by Eq. (3), respectively.

The classification criteria of SPI, sc-PDSI, CI, and s-CI in China are shown in Table 3.

2.3 Methods

2.3.1 Mann–Kendall test (MK)

The nonparametric Mann–Kendall test was used to detect the variable trends (Mann 1945; Kendall 1948). The null hypothesis of the test is that a dataset of a generic variable is independent and has no trend. When the p value of the standardized statistic Z is higher than the selected significance level, the null hypothesis will be rejected. The test statistic Z is estimated by the following formula (Hirsch et al. 200 1982):

$$Z = \begin{cases} \dfrac{S-1}{\left(\mathrm{Var}(s)^{1/2}\right)} & \text{if } S > 0 \\[2mm] 0 & \text{if } S = 0 \\[2mm] \dfrac{S+1}{\left(\mathrm{Var}(s)^{1/2}\right)} & \text{if } S < 0 \end{cases} \tag{(1)}$$

Table 3 The classification standards of the SPI, sc-PDSI, CI, and s-CI

Drought classification	SPI	sc-PDSI	CI	s-CI
Normal	SPI>−0.5	sc-PDSI>−1.0	CI>−0.6	CI>−0.6
Mild drought	−1.0<SPI≤−0.5	−2.0<sc-PDSI≤−1.0	−1.2<CI≤−0.6	−1.2<CI≤−0.6
Moderate drought	−1.5<SPI≤−1.0	−3.0<sc-PDSI≤−2.0	−1.8<CI≤−1.2	−1.8<CI≤−1.2
Severe drought	−2.0<SPI≤−1.5	−4.0<sc-PDSI≤−3.0	−2.4<CI≤−1.8	−2.4<CI≤−1.8
Extreme drought	SPI≤−2.0	sc-PDSI≤−4.0	CI≤−2.4	CI≤−2.4

where

$$\mathrm{Var}(s) = \left\{ n(n-1)(2n-5) - \sum_{r} t(t-1)(2t5) \Big/ 18 \right\} \qquad ((2))$$

$$S = \sum_{K=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}\left(x_j - x_k\right) \qquad ((3))$$

$$\mathrm{Sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \qquad ((4))$$

where x is the variable, a sample of n independent and identically distributed random variables, t is the extent of any given tie, and $\sum_t$ presents the summation over all sites.

In addition, the trend magnitude β, an estimator developed by Hirsch et al. (1982), was used in this study. β could be defined as the following:

$$\beta = \mathrm{median}\frac{(x_j - x_i)}{(j-i)} \qquad (5)$$

where $1<i<j<n$, and the slope estimator β is the median over all possible combinations of pairs for the whole dataset (Gan 1998). More details on the MK test can be found in Yue et al. (2002), Song et al. (2009), and Liu et al. (2012a, b).

Many studies have indicated that the serial correlation may alter the variance of MK. In particular, a positive serial correlation increases the variance of MK with a consequent increase in the probability to reject the MK null hypothesis. In addition, the trend also alters the estimation of serial correlation. To reduce the effect of serial autocorrelation on MK test, the "Trend-Free-Pre-Whitening" procedure was applied in this study (Yue et al. 2002).

2.3.2 Empirical orthogonal function

The empirical orthogonal function (EOF) is a statistical technique that linearly transforms an original set of variables to a substantial smaller set of uncorrelated variables, but the smaller variables can still represent most information of the original variables (Kutzbach 1967; North et al. 1982). Essentially, the EOF reduces the data dimensionality, and the smaller set of uncorrelated variables is much easier to

understand and further analyze than a larger set of correlated variables. Therefore, the EOF has become a popular tool in meteorology, geology, and geography (Kim and North 1993; Tomozeiu et al. 2002; Yoo and Kim 2004; Hisdal and Tallaksen 2003). More details on EOF can be found in Kim et al. (2011).

3 Results and discussion

3.1 Comparison of different drought indices

3.1.1 Qualitative comparison of indices with historical drought records

The numbers of spring drought records and the drought events predicted via indices in April and May were counted for the 1992–2010 period for the SNP (Table 4). The results indicated that the four indices (SPI, sc-PDSI, CI, and s-CI) generally performed well, although there were some drawbacks associated with each index when applied for the detection of spring drought across the Songnen Plain.

The SPI did not identify all the expected changes of drought events, especially at Baicheng station and Changling station.

Table 4 The comparison of the drought indices and spring drought records from 1992 to 2010 in the SNP

Station	Month	SPI	sc-PDSI	CI	s-CI
Nenjiang	April	0/2	0/2	1/2	0/2
	May	3/5	1/5	3/5	4/5
	April and May	3/7	1/7	4/7	4/7
Fuyu	May	1/1	1/1	1/1	1/1
Harbin	May	3/4	3/4	4/4	3/4
Baicheng	April	1/1	0/1	1/1	1/1
	May	0/2	0/2	0/2	2/2
	April and May	1/3	0/3	1/3	3/3
Changling	April	0/1	1/1	1/1	1/1
	May	7/11	9/11	9/11	10/11
	April and May	7/12	10/12	10/12	11/12

The denominator of the fraction indicates the number of spring drought records up to mild drought. The numerator of the fraction indicates the number of drought indices up to mild drought severity

These results may be because that SPI is based solely on precipitation, but other factors (e.g., evapotranspiration) that affect local water balance can also eventually result in water deficiency (Zhai et al. 1999).

The sc-PDSI also did not completely identify drought events in April and May, especially at Nenjiang station and Baicheng station (Table 4). The reason may be the effects of seasonal frozen water or snowmelt, as the sc-PDSI did not reflect reasonable soil moisture conditions during the spring months in the SNP (Dai et al. 2004). In this context, there are some difficulties in applying the sc-PDSI for spring drought monitoring in the SNP.

The CI, which considers the influences of the recent and accumulated precipitation situation and regional water balance, performed better than the SPI and sc-PDSI, especially at the Nenjiang station and Harbin station (Table 4).

Unlike the CI, the s-CI introduced the impacts of precipitation in the previous autumn (SPI3$_{11}$) into the calculations. Table 4 shows that s-CI identified the most important droughts in the 1990s and 2000s. The index performed better than the CI at Baicheng station and Changling station and performed similar to the CI at Nenjiang station and Fuyu station. At Harbin station, the spring drought events indicated by s-CI were slightly fewer than the CI but were equivalent to those indicates by the SPI and sc-PDSI. Although there were still shortcomings with using the s-CI, the index was generally superior in evaluating spring droughts than the other three commonly used indices.

3.1.2 Quantitative comparison of indices with relative soil moisture

Soil moisture not only controls the interaction of the land with the atmosphere but also plays an important role in the process of converting precipitation into runoff and groundwater storage. High soil moisture may promote vegetation growth and consequently leads to high evapotranspiration. Conversely, a soil moisture deficit may result in more infiltration and less runoff. Therefore, soil moisture is a significant hydrological variable that is related to droughts (Tang and Piechota 2009).

Table 5 shows that the correlations between the different layers of relative soil moisture were all significant at a significance level of 0.05 at the Nenjiang, Baicheng, and Changling Stations, which represented the high amounts of interflow between soil layers.

Specifically, at Nenjiang station, the correlation coefficients between the relative soil moisture and drought indices were ranked as follows: s-CI>CI>sc-PDSI>SPI. Although s-CI did not pass the 95 % test, the index improved correlations much greater than the other three indices. At Baicheng station, there were high correlations between the s-CI and relative soil moisture at different layers. In addition, the

Table 5 Correlations between relative soil moisture and drought indices of April of 1992–2010 in the SNP

Station	Soil layer	20 cm	SPI	sc-PDSI	CI	s-CI
Nenjiang	10 cm	**0.86**	0.26	0.30	0.39	0.63
	20 cm		0.15	0.14	0.24	0.60
Baicheng	10 cm	**0.81**	0.01	0.18	0.08	**0.58**
	20 cm		−0.08	0.22	−0.02	**0.67**
Changling	10 cm	**0.74**	0.36	0.24	0.44	0.42
	20 cm		0.26	0.25	0.29	0.34

The bold numbers indicate that correlation is significant at a 0.05 significance level

correlation coefficient between the s-CI and relative soil moisture was slightly lower than that between CI and the relative soil moisture at the 10-cm soil layer, whereas it was higher than that between the CI and relative soil moisture at the 20-cm soil layer for Changling station. However, neither value passed the 95 % test. It should be pointed out that the collected relative soil moisture series at Nenjiang station was shorter than that from Baicheng station. It may be the possible reason why the correlations in Nenjiang station data at the 10-cm soil layer were higher than that in Baicheng station, but the data correlations in Nenjiang station did not pass the 95 % test. On the whole, s-CI obviously improved the detection of spring drought in April because it accounted for the impact of land memory on spring drought conditions.

Table 6 summarizes the correlations between different soil layers and between the relative soil moisture and drought indices in May. As related by the table data, there was a high amount of interflow between two nearby soil layers in May at five stations (Nenjiang, Fuyu, Baicheng, Changling, and Harbin).

At Nenjiang station, the correlations between the s-CI and the relative soil moisture at the 10-, 20-, and 50-cm layers were 0.51, 0.64, and 0.24, respectively. Moreover, the correlations at 10 cm and 20 cm were significant at a level of 0.05. Although the correlation at 50 cm did not pass the 95 % test, the s-CI performed better than the SPI, sc-PDSI, and CI. At Fuyu station, the highest correlation was between the relative soil moisture and the sc-PDSI. The s-CI did not improve the correlation obviously in May, but the index performed better than the SPI and CI. At Harbin station, the correlations between the relative soil moisture for the 10-cm layer, 20-cm layer, and the SPI and CI both passed the 95 % test. The s-CI higher correlated with the relative soil moisture at the 20- and 50-cm layers than other three indices. It was worth noting that the s-CI significantly improved the correlations for all the observed soil layers at Baicheng and Changling stations in May and notably improved the identifications of spring drought.

Table 6 Correlation between relative soil moisture and drought indices of May of 1992–2010 in the SNP

Station	Soil layer	20 cm	50 cm	70 cm	SPI	sc-PDSI	CI	s-CI
Nenjiang	10 cm	**0.85**			0.42	0.11	0.45	**0.51**
	20 cm		**0.76**		0.35	0.08	0.37	**0.64**
	50 cm				−0.10	0.01	−0.03	0.24
Fuyu	10 cm	**0.93**			0.40	**0.72**	0.44	0.38
	20 cm		**0.90**		0.32	**0.70**	0.41	0.28
	50 cm			**0.82**	0.24	**0.58**	0.27	0.37
	70 cm				0.07	0.31	0.09	0.38
Harbin	10 cm	**0.85**			**0.64**	0.47	**0.81**	0.56
	20 cm		**0.87**		**0.63**	0.40	**0.67**	**0.71**
	50 cm				0.53	0.40	0.47	**0.73**
Baicheng	10 cm	**0.81**			**0.67**	**0.47**	**0.62**	**0.85**
	20 cm		0.73		0.25	0.40	0.26	**0.70**
	50 cm				0.08	0.24	0.08	**0.48**
Changling	10 cm	**0.84**			**0.63**	0.02	**0.59**	**0.74**
	20 cm		0.78		**0.51**	0.10	**0.58**	**0.59**
	50 cm				0.33	0.44	0.31	**0.57**

The bold numbers indicate that correlation is significant at a 0.05 significance level

3.2 Spatial–temporal variability of spring drought based on the s-CI

3.2.1 Interannual variability of s-CI series

The interannual variability (1959–2010) of the s-CI in April and May for the SNP are shown in Fig. 2. The smaller value of s-CI indicates a greater severity of drought. The mean s-CI in April ranged from −1.42 (1997) to 0.56 (1983) with an average of −0.62, whereas in May it ranged from −1.68 (2002) to 0.58 (1960) with an average of −0.58. In April, there were 4 years that experienced moderate droughts and 24 years that experienced mild droughts. Moreover, there were 6 years that experienced moderate droughts and 18 years that experienced mild droughts in May. The
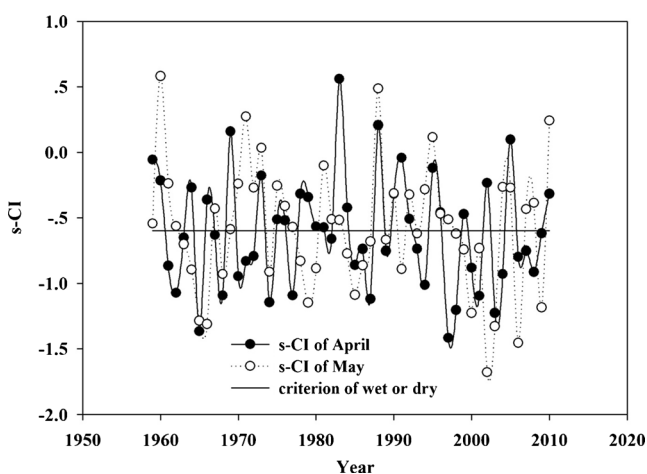
Fig. 2 Interannual variability of the s-CI series in the SNP

average standard deviation of the s-CI in April and May was 0.43 and 0.48, respectively.

During different decades, the s-CI in April were ranked as follows: 2000s<1970s<1960s<1990s<1980s, whereas in May the rankings were as follows: 2000s<1960s<1980s< 1990s<1970s. In 1960s, 1970s, and 1990s, the s-CI in April was lower than that of May, whereas the s-CI in May was smaller in the 1980s and 2000s than the April value.

3.2.2 Trends of s-CI series by Mann–Kendall test

Trends of s-CI in April (Fig. 3) and May (Fig. 4) were evaluated at 31 stations (17 stations within and 14 stations around the SNP) by the MK test. It should be noted that the downward trend of s-CI indicates that the spring drought will become increasingly severe. In April or May, more than 50 % of stations had a downward s-CI trend during 1959–2010, 1970–2010, and 1980–2010, indicating that the most recent spring droughts (2000s) were the most severe. The results obtained were consistent with other spring drought studies in northeast China (Zou and Zhang 2008; Zou et al. 2010; Xi et al. 2008; Li et al. 2006; Zhai et al. 2010). In April, the number of stations with a downward s-CI during 1970–2010 was less than the number during 1959–2010 and 1980–2010, which indicates that the weather was driest in the 1970s compared with the 1960s and 1980s. However, In May, there were more stations with a downward s-CI during 1970–2010 than during 1959–2010 and 1980–2010. This indicates that the weather was wetter in the May of the 1970s compared with Mays of other decades.

During 1980–2010, there were fewer stations with a downward trend in May than in April, which indicates that the weather was drier in May compared with that in April of

Fig. 3 Trends for the April s-CI
series in the SNP
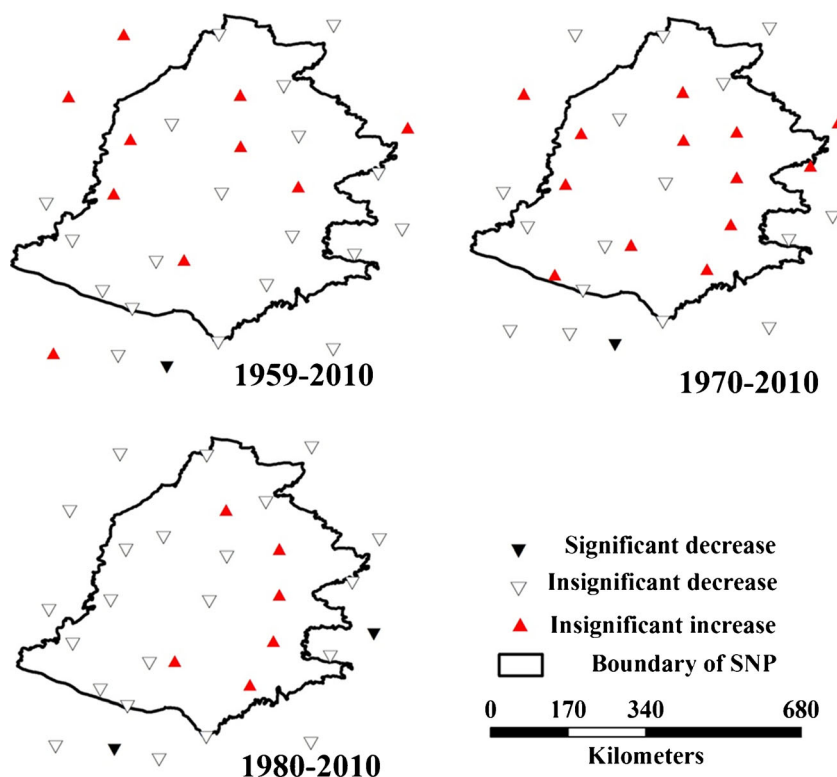
the 1980s. However, there were more stations with downward trends in May than in April during 1959–2010 and 1970–2010. Moreover, 20 % of the stations, which were in the central and southern areas of the SNP, presented a significant downward at a test level of 0.05 during 1970–2010. These results indicate that the weather was wetter in May than that in April of 1960s and 1970s. These results were consistent with the results obtained in "Interannual variability of s-CI series" section.

Fig. 4 Trends for the May s-CI
series in the SNP
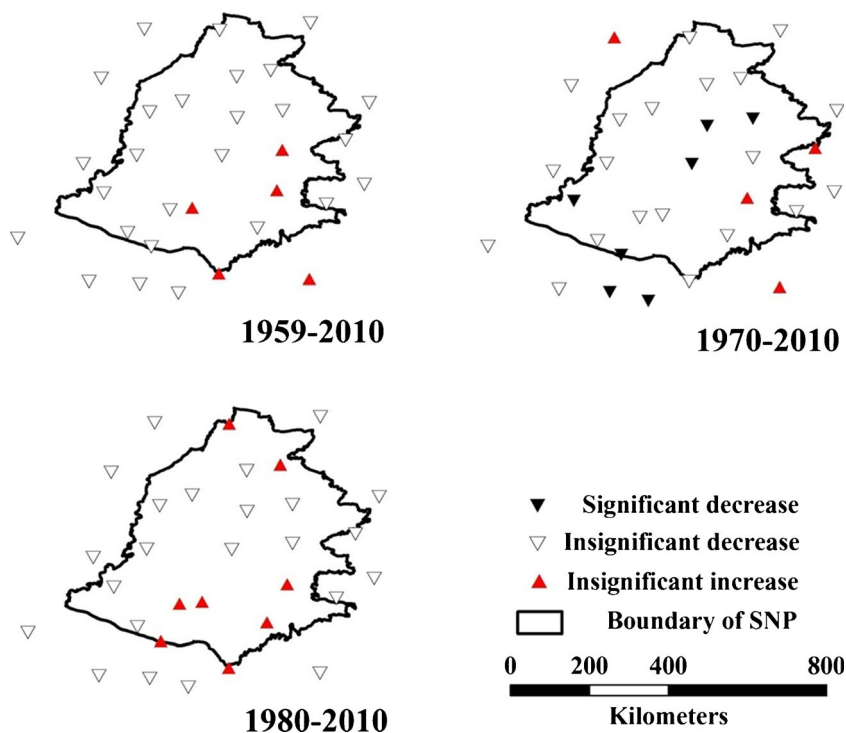
3.2.3 Spatial–temporal variability of s-CI series by empirical orthogonal function (EOF)

The EOFs of the s-CI series were calculated during 1959–2010. The proportions of variance explained by each EOF of April and May are given in Fig. 5. The first two EOFs in April explained approximately 72 % and 7 % of total variance, whereas the values explained approximately 68 % and 9 % of total variance in May, respectively. It is generally assumed that those EOFs, whose accumulated variance is more than 70 % of the total variance, have significance in explaining the original data (Kim et al. 2011). In this study, the first two EOFs explained 79 % and 77 % of the total variance in April and May, respectively. Therefore, the first two EOFs were used in this study to explain the original data.

Figure 6 shows the shapes of the first two EOFs in April and May for the SNP. Specifically, the first EOFs in April and May both displayed east–west drought patterns. The center of the first EOF in April was near Tailai station (value +0.2011), whereas in May, the center was at Baicheng station (value +0.2063). These results appear to be in accordance with the spatial distribution of precipitation in the SNP (Li et al. 2006). In addition, the first EOF values in April and May were both positive, which indicates the spring drought was affected by the same large-scale climate.

Precipitation is a key factor affecting drought. Consequently, the atmospheric circulation affecting precipitation may have similar influences on drought (Liu et al. 2012b). Of E-type, W-type, and C-type atmospheric circulation, E-type and W-type are the main types affecting the precipitation in the SNP. When the E-type atmospheric circulation strengthens, wet air brings favorable conditions for precipitation. In contrast, when the E-type circulation weakens and the W-type atmospheric circulation develops, the vapor radical transport will be hindered, bringing less precipitation (Zhang and Gao 1994). The W-type circulation is a dominant type in the spring and autumn of the SNP (Zhang and Fang 1959). Consequently, spring drought frequently occurs in the SNP. In addition, the similar patterns of EOFs in April and May indicated they were both affected by the W-type circulation.

The second EOFs in both April and May indicated that drought severity had obvious north–south differences. The second EOFs in the northern SNP for April and May were both positive (center station, Beian), whereas in the southern SNP, the second EOFs were both negative (center station, Changling). The zero contours for April and May were both located around Tailai–Anda–Harbin, which indicated an approximately east–west direction.

Coefficient time series, which is derived by multiplying the matrices, are frequently used to indicate the variance assigned to each EOF. As seen in Fig. 7, the first EOF showed more fluctuations than the second EOF. There were 30 positive values out of 52 coefficients for the second EOF, whereas there were five positive values for the first EOF in April. The ratio was 28 to 52 in the coefficients of second EOF, whereas the ratio was 6 to 52 for the first coefficients of EOF in May. Moreover, the time series of the first EOF coefficient indicated continuous spring drought characteristics. For example, in 1960–1968, 1970–1982, and 1992–2004 in April and 1961–1970, 1974–1987, and 1996–2009 in May, there were continuous spring drought conditions. These results are consistent with Sun and Bai (2005), who

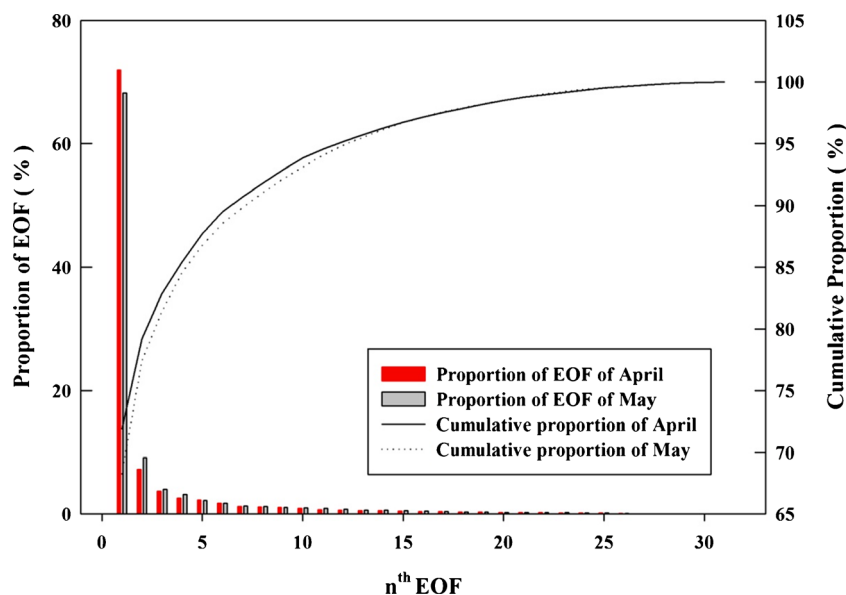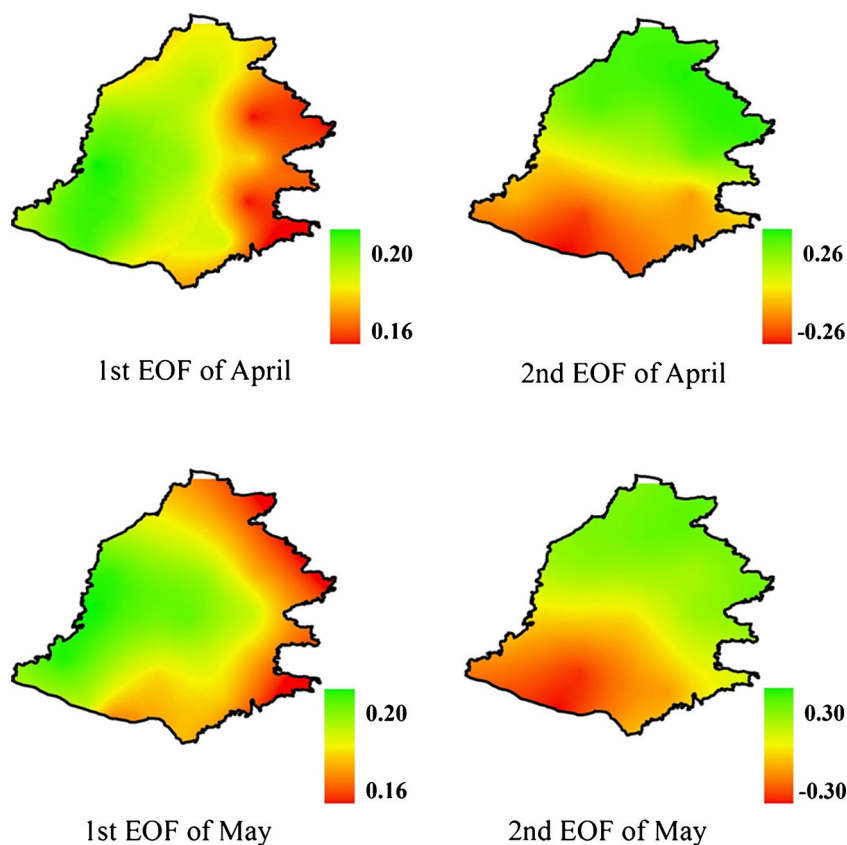**Fig. 5** Proportion of variance accounted for by each EOF of April and May in the SNP

Fig. 6 Shapes of the first and second EOFs of April and May in the SNP

1st EOF of April

2nd EOF of April

1st EOF of May

2nd EOF of May

indicated that spring drought was frequent in the SNP (Sun and Bai 2005).

Negative trends for the first EOFs (Fig. 7) in April and May were detected with a decrease of 0.011 and 0.0246 for 1959–2010, respectively. Moreover, the downward trend of drought in April was more pronounced than that of May. These results are consistent with the MK results of the s-CI for April and May. A positive trend of the second EOF in April was detected (0.0161), whereas a slight decrease trend in May was detected (0.0078). The different trends of the second EOFs in April and May could be related to different dominant contributing factors affecting the evapotranspiration in April (increasing temperature) and May (decreasing wind) (Meng and Mo 2012).

4 Conclusions

In this study, a spring-composite index (s-CI), which accounted for the precipitation of the previous autumn, was developed based on the CI and compared with other commonly used drought indices. The spatial–temporal variability for spring drought based on the s-CI was then explored in the Songnen Plain. Three main conclusions could be drawn:

1. Compared to the other three drought indices examined, the proposed s-CI could identify a higher number of important droughts during the 1990s and 2000s and more notably correlated with the measured relative soil moisture at different layers at many stations over the SNP. Consequently, the s-CI could be used as a measurement for detecting, monitoring, and exploring spring drought in the SNP under global warming. However, there were still some uncertainties: (1) uncertainties related to the selected stations, (2) uncertainties related to the spring disaster records, (3) uncertainties related to the relative soil moisture data, and so on. For uncertainties 1–3, there were certain amounts of subjectivity. For example, the relative soil moisture data were recorded based on different plant types (e.g., spring corn, spring wheat, and bean). However, there were efforts made to reduce the error via selecting more complete records from the same type of plants.

2. The recent spring droughts (2000s) were the most severe. The weather was driest in April of the 1970s compared with that in the 1960s and 1980s. However, the weather was wetter in May of the 1970s compared with Mays of the other decades. In the 1980s, the weather was drier in May compared with that of in April,

Fig. 7 Coefficient time series of the first and second EOFs of April and May in the SNP
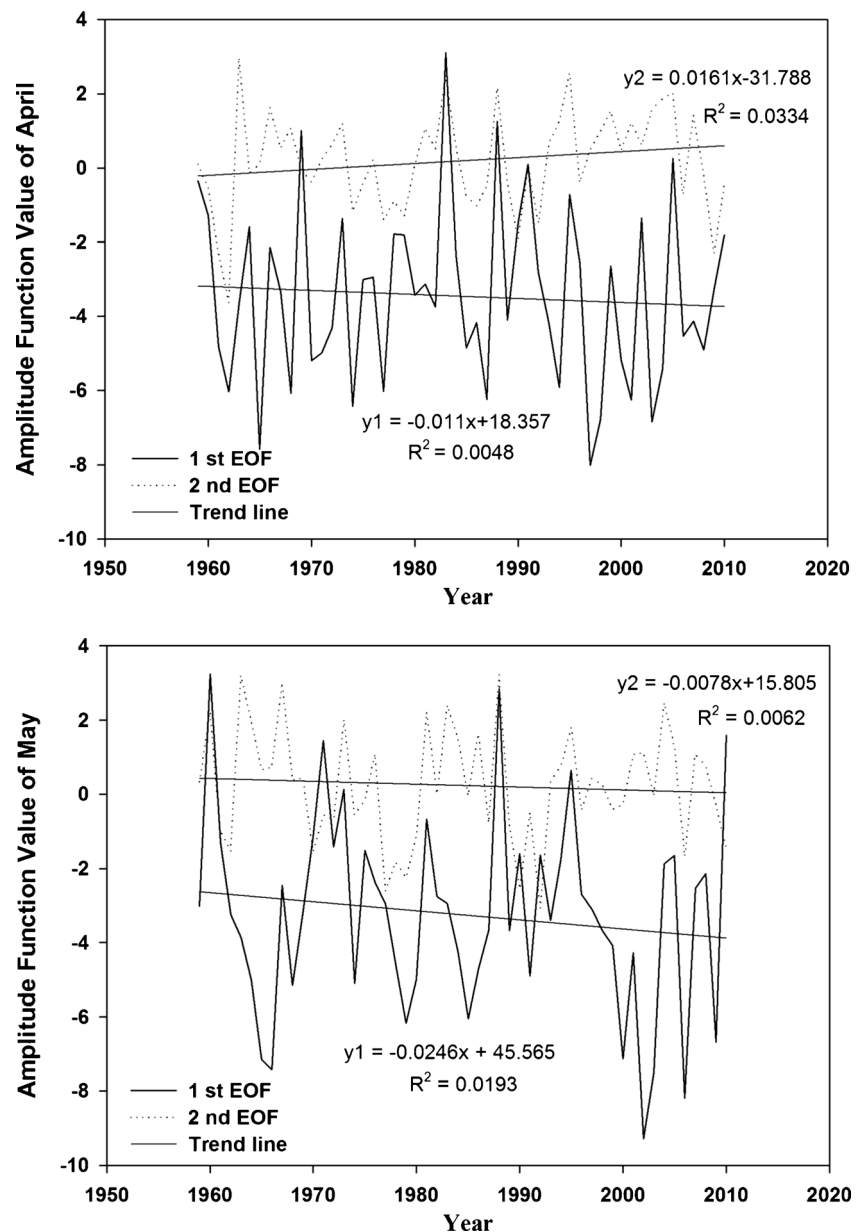
whereas in the 1960s and 1970s, the weather was wetter in May than that of April.

3. The first two EOFs for April and May were selected in this study to identify the spatial–temporal variations of the predominant components of the s-CI. The results indicated that the first EOF values in both April and May indicated east–west drought patterns for the SNP. Moreover, the first EOF values of April and May were all positive, which indicated that the spring drought was affected by similar large-scale circulation patterns. In addition, the second EOFs in both April and May indicate north–south drought patterns. Furthermore, the time series of the first EOF coefficient indicated more fluctuations than the

second series and also indicated continuous spring drought.

There are many scientific debates about which climate parameters (e.g., precipitation and evapotranspiration) are the most important factors in influencing drought severity (Vicente-Serrano et al. 2010). The importance of precipitation in explaining drought variability is generally accepted. However, it is not well known how other factors (e.g., temperature) affecting evapotranspiration processes can influence the usable water resources. Although the s-CI could identify the most important and severe drought events and presented improved correlation with relative soil moisture compared with other commonly used indices,

further studies are still required to understand the mechanisms of these phenomena.

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