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# Long-term Trend and Variability of China's Arid Climate and Drought Area based on the Standardized Precipitation Index

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**Abstract**—Drought is one of the major agricultural and meteorological disasters in China that occurs at high frequency, affects wide areas, and causes considerable agricultural loss. Research on the long-term spatiotemporal variability of arid climate and drought area in the context of global climate change is important and practically significant to the intention to cope with drought. Standardized precipitation index (SPI) was calculated using long-term monthly data of surface precipitation with  $0.5^\circ \times 0.5^\circ$  resolution at 12-month timescales. The capacity of the SPI index to describe arid climate was verified using three drought cases that occurred in Southern China in the early 2000s. The spatiotemporal variability of China's arid climate and drought area from the perspective of meteorological drought was analyzed. All categories of drought (i.e., mild, moderate, severe, and extreme) exhibited slight downward trend in terms of drought area, but variation was observed from region to region. Over the past 50 years, Southwest and Northeast China experienced more arid, while Southeast and Northwest China experienced the opposite.

**Keywords**—drought; spatiotemporal evolution; standardized precipitation index; timescale

## I. INTRODUCTION

Drought is one of the major agricultural and meteorological disasters in China that occurs at the highest frequency, affects the widest areas, and causes the largest agricultural loss [1]. The affected drought area, damaged area and damaged rate were increasing over the past 50 years [2]. Therefore, detecting and monitoring the spatiotemporal evolution of drought is important in agricultural agrometeorology. Drought index is a valuable quantitative method for monitoring and evaluating drought because of its clear and simple operation. Scientists have developed various indices to identify and determine occurrence and intensity of droughts [3-6]. Among these, the standardized precipitation index (SPI) attracted special attention when it was introduced by McKee et al. [4, 7]. This method has been widely recommended because it offers several advantages such as easy data acquisition, simple calculation, effective quantitative assessment, and wide spectrum of time scales ranging from

one to 72 months [8]. SPI was applied to analyze regional droughts in Eastern China [9, 10], Iran [11, 12], Czech [13], the United States [14], and South America [15]. Many scientists have analyzed regional drought characteristics, such as drought frequency, duration, and intensity using the SPI index. However, few studies on the trend and variation of drought area percentage using SPI index have been reported; this is an important concern of policy makers.

This study aimed to (1) verify the applicability of SPI index to detect and monitor drought occurrence in China, (2) analyze the long-term trend of arid and humid climate, and (3) evaluate variations and trends of different drought types.

## II. MATERIALS AND METHODS

### A. Study area and data source

China's territory spans many degrees of latitude and has complex terrain. Thus, a huge regional difference in climate and farming systems can be observed. According to the characteristics of each area of agricultural production, this research covered the entire territory of China, which is subdivided into 10 regions, namely, Northeast China (NE), Northern plateau (NP), Yellow-Huai-Hai River basin (YH), middle and low reaches of the Yangtze River (YR), South hillside region (SH), South China (SC), Sichuan and Shaanxi basin (SS), Yunnan-Guizhou plateau (YG), Northwest China (NW), and the Qinghai-Tibet plateau (QT) (Fig. 1).

Analysis of droughts was performed using 50-year record of monthly precipitation from 1961 to 2010. The monthly precipitation dataset with  $0.5^\circ \times 0.5^\circ$  grid was provided by the National Climate Center of the China Meteorological Administration (CMA); this dataset was produced by the thin-plate spline interpolation method (TPS), which was implemented through rigorous quality control using data obtained from 2,400 meteorological observation stations.

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Fig. 1. Map showing the 10 major agricultural planting regions

Note: The Roman numerals denote the 10 agricultural regions: I = Northeast China; II = Northern Plateau; III = Yellow-Huai-Hai River basin; IV = Middle and Low Reaches of the Yangtze River; V = South Hillside region; VI = South China; VII = Sichuan and Shensi Basin; VIII = Yunnan-Guizhou plateau; IX = Northwest China; and X = Qinghai-Tibet plateau.

### B. The SPI index

Precipitation is the primary factor in the formation and persistence of drought conditions, and evapotranspiration is an important variable [16]. Acquiring reliable data from observed and modeled evapotranspiration measures across China is difficult; therefore, drought index based on precipitation was chosen for this study.

The standardized precipitation index (SPI) was designed by McKee et al. [4] to quantify precipitation deficit for multiple timescales and identify dry and wet events and their severity [17]. The SPI is a meteorological index that is based on the probability distribution of precipitation; this probability is normalized using Gaussian function [18]. SPI negative values indicate drought and SPI positive values indicate wetness. Different types of drought were identified using predefined thresholds of SPI, as recommended by CMA (Table 1).

SPI is a dimensionless index; thus, different drought types can be monitored, such as the shorter timescales for agricultural or meteorological drought and the longer timescales for hydrological drought [19]. A window length of 12 months (SPI12) proved to be a suitable timescale because it captured low frequency variability, avoided the possibility of seasonal variations, and allowed direct comparison with results from other studies [20, 21]. This study primarily focused on the analysis of the long-term aspect of dryness and wetness, and not on short timescales.

TABLE I CLASSIFICATION OF SPI AND DROUGHT CATEGORY

Symbol	Category	SPI	Probability of occurrence
D0	No drought	$-0.5 < \text{SPI}$	0.691
D1	Mild drought	$-1.0 < \text{SPI} \leq -0.5$	0.150
D2	Moderate drought	$-1.5 < \text{SPI} \leq -1.0$	0.092
D3	Severe drought	$-2.0 < \text{SPI} \leq -1.5$	0.044
D4	Extreme drought	$\text{SPI} \leq -2.0$	0.023

### C. Drought area

The area of each grid point varied with latitude; therefore, drought area was calculated from each grid point using weight that depended on the latitude located at the center of the grid point [22]. Thus, drought area in the latitude-longitude grid-point-boxes should be weighted.

$$A_i = x \times y \times 111.0 \times 111.0 \times \cos \phi_i \quad .1 \quad .(1)$$

where  $A_i$  is the area of the grid point  $i$ ;  $x$  and  $y$  are the grid spacing of the latitude and longitude, respectively; 110.0 (km) is the distance of the  $1^\circ$  grid spacing from the equator; and  $\cos \phi_i$  is the weight based on the latitude at the center of each grid point.

### D. Trend-free pre-whitening Mann-Kendall

The Mann-Kendall (MK) statistical test is one of the widely used non-parametric tests to detect trends in recorded meteorological and hydrological time series [23, 24]. The advantages of this test are the absence of requirements for data that have confirmed to any particular distribution and the low sensitivity to abrupt breaks due to inhomogeneous time series [25]. However, the MK test's requirement for independent time series is often rejected because of the presence of serial correlation in the time series that can weaken the accuracy of the test [26]. Owing to this situation, trend-free pre-whitening Mann-Kendall (TFPW-MK) was developed by Yue et al. [27, 28] to eliminate serial correlation prior to using the MK test. The calculation procedure of the TFPW-MK test is presented in previous studies by Kumar et al. (2009) [29].

## III. RESULTS AND DISCUSSION

### A. Verifying the capacity of SPI to monitor drought events in Southeast China

The SPI12 was used to describe three major drought events in Southern China that occurred in the early 21st century. Subsequently, the results were utilized to verify the applicability of SPI12 in the analysis of drought. Figure 2 shows the SPI12 values at different time periods, including November 2004, August 2006, and April 2010. The applicability of SPI12 in the analysis of drought can be proven by comparing the data (i.e., drought area and severity) obtained from SPI12 with the actual occurrence. In 2004, South China suffered the worst autumn drought over the past 50 years, affecting mainly the middle and lower reaches of the Yangtze River and Southern China, specifically the provinces of Zhejiang, Jiangxi, Fujian, and Guangdong. A climate characterized by high temperature and less rainfall was experienced from June to August of 2006, which caused extreme summer drought in the east of Sichuan and Chongqing. In early 2010, five southwest provinces suffered a once-in-a-century severe spring drought, affecting areas such as Yunnan, Guizhou, Sichuan, Chongqing, Guangxi, Hunan, and Hubei. Among these areas, Yunnan and Guizhou were most affected. The above observations using SPI12 index were consistent with actual observations. This consistency

demonstrated that SPI12 has the ability to monitor drought in China.

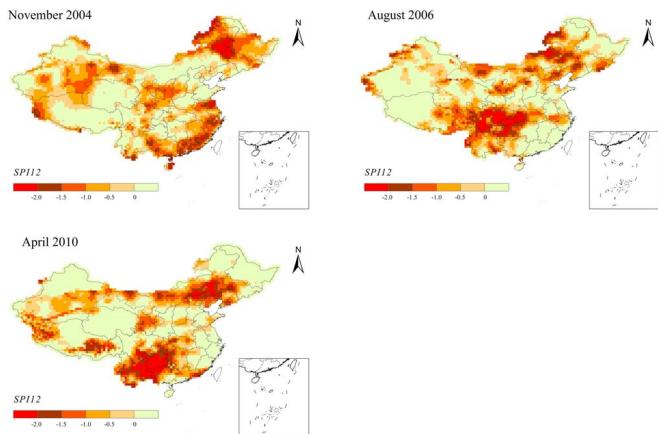


Fig. 2 SPI12 indices obtained in November 2004, August 2006, and April 2010

### B. Long-term trend of dry and wet climate in China

TFPW-MK test was used to derive the trend of the SPI12 from 1961 to 2010 (Fig 3). Significant difference in terms of the national distribution of arid and humid climate change among the different areas was observed. The SPI12 decreased in the Southwest region, northern part of the North plateau, Northeast China, and Eastern Inner Mongolia; all these places experienced significant drought ( $P < 0.01$ ). A sharp decline in the SPI12 was observed in the Loess Plateau, East Sichuan, and junction of Yunnan and Guizhou whereas a slight increase in the SPI index was observed in the middle-lower Yangtze area, which is composed of Jiangxi, Hubei, Hunan, Zhejiang, and Fujian. In the southeastern coast of China, northern Tibetan Plateau, and Northern Xinjiang, the SPI12 increased rapidly, which indicates an obvious wetting trend. The nationwide SPI12 changed significantly and passed a significant test of  $\alpha=0.01$  aside from part of Jiangxi and Guangdong.

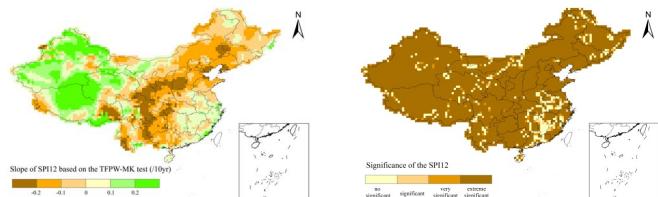


Fig. 3 Trend and significance of SPI12 based on the TFPW-MK test  
Note: Extremely significant at 99% confidence level; very significant at 95% confidence level; significant at 90% confidence level

### C. Drought area and changing trends

Figure 3 shows the trend of drought area percentage in relation to territory. The nationwide arid areas showed significant downward pattern with a slope of  $1.56\%/10\text{yr}$ . The largest decline in area was observed in the moderate drought area, with a slope of  $0.53\%/10\text{yr}$ . This was followed by the

mild drought and severe drought areas, with slopes of  $0.42\%/10\text{yr}$  and  $-0.35\%/10\text{yr}$ , respectively. Extreme drought area exhibited the lowest decline, with a slope of  $0.26\%/10\text{yr}$ . From the point of decadal variation, nationwide drought area with a proportion of more than 30% occurred in the 1960s, late 1970s to the early 1980s, and early 2000s, which was larger than those of the other years.

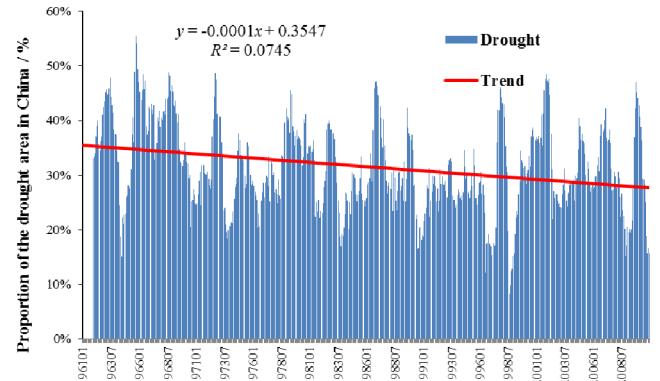


Fig. 4 Proportions of drought area to territory  
Note: the drought area is the sum of the mild, moderate, severe, and extreme drought areas

Over the past 50 years, drought area increased significantly ( $P < 0.01$ ) in the following areas: NE, NP, YR, SS, and NW. Among these areas, the Sichuan basin and Northern plateau exhibited high increase in drought area percentage, which was more than  $3.5\%/10\text{yr}$ . Drought area decreased in YH, SH, SC, and YG. In these areas, the decrease in YH and SH was more than  $5\%/10\text{yr}$  in. Other observations were as follows: (1) Percentage of drought areas in NE significantly increased ( $P < 0.01$ ) by  $1.93\%/10\text{yr}$ , of which the highest percentage of drought area was observed in early 2008 (80%), followed by the beginning of 1980 (77%). Fluctuations in the percentage of drought area were observed to be relatively high from late 1970s to early 1980s. (2) Percentage of drought areas in NP also significantly increased ( $P < 0.01$ ) by  $3.71\%/10\text{yr}$ . In particular, the drought area percentage increased by 79% in the autumn of 1972, and reached 77% in 1966. (3) Drought area percentage in YH showed a decreasing trend in the recent 50a ( $-5.98\%/10\text{yr}$ ). In these areas, mild drought decreased by  $2.02\%/10\text{yr}$  and moderate drought by  $0.56\%/10\text{yr}$ . Severe and extreme drought did not change significantly. A range of drought occurred in 2002, 2002, and 1981, but the duration was not extensive. In 1966 and 1967, drought lasted for more than one year. (4) The areas of the middle and lower reaches of the Yangtze River showed a significant reduction in the percentage of drought regions ( $-1.24\%/10\text{yr}$ ). The percentage of drought area was at its peak in 1966, 1967, 1979, and 2000. (5) The percentage of drought area in SH significantly declined by  $-5.01\%/10\text{yr}$ . Drought area percentage was 90% in 1963 and 2004. (6) The climate characterized with drought or wetness frequently conversed in SC, and the huge variations of drought area could be detected. Percentage of drought area showed slight decreasing trend

TABLE II SLOPE OF DROUGHT AREA PERCENTAGE BASED ON SPI12

Area	Slope of drought percentage (%/10yr)				
	Mild drought	Moderate drought	Severe drought	Extreme Drought	Drought
China	-0.42***	-0.53***	-0.35***	-0.26***	-1.56***
NE	0.09	0.60***	0.62***	0.62***	1.93***
NP	1.14***	1.68***	0.82***	0.07	3.71***
YH	-1.86***	-2.02***	-1.38***	-0.72***	-5.98***
YR	1.37***	0.81***	0.08	-0.11	2.15***
SH	-1.23***	-2.07***	-0.97***	-0.73***	-5.01***
SC	0.44	-0.94***	-1.13***	-0.64***	-2.26***
SS	1.39***	1.18***	1.09***	0.98***	4.64***
YG	-0.32	-0.2	-0.37	-0.50***	-1.39
NW	0.99***	1.06***	1.01***	0.73***	3.78***
QT	0.22	0.68***	0.25	-0.19	0.96

Note: (1) NE refers to Northeast China; NP refers to the Northern plateau; YH refers to the Yellow-Huai-Hai River basin; YR refers to the middle and low reaches of the Yangtze River; SH refers to the South hillside region; SC refers to South China; SS refers to the Sichuan and Shaanxi basin; YG refers to the Yunnan-Guizhou plateau; NW, refers to Northwest China; and QT refers to the Qinghai-Tibet plateau. (2) \* Significant at  $P < 0.1$ ; \*\* significant at  $P < 0.05$ ; \*\*\* significant at  $P < 0.01$

(2.26%/10yr). Drought area percentage was 85% in 1963 and decreased to 60 % in 2004. (7) The percentage of drought area in SS significantly increased ( $P < 0.01$ ) by 4.64%/10yr. (8) The drought area percentage in YG decreased significantly by 2.92%/10yr. In particular, the extreme drought area declined by 0.50%/10yr. (9) In spite of the more humid climate in NW and QT over the past 50 years, the drought area percentage in NW and QT increased by 3.78%/10yr and 0.96%/10yr, respectively, because of the weaker drought severity.

#### IV. CONCLUSIONS

We verified the applicability of the SPI to monitor China's dry climate, and analyzed variations and trends in drought areas of 10 major agricultural regions over the past 50 years. The main conclusions are as follows: (1) The study validated the capacity of the SPI index to assess drought climate in our country. (2) The climate in Southwest and Northeast China became more arid and that in Southeast and Northwest China became more humid over the past 50 years. This result is consistent with previous studies [30, 31]. (3) Overall, the drought area percentage exhibited downward trend. Among the drought categories, the moderate drought areas decreased by 0.53%/10yr, the mild and severe drought areas decreased by 0.42%/10yr and 0.35%/10yr, respectively; however, inconsistencies were observed in the trend of drought area percentage in the regions.

SPI offered advantages for analyses that solely relied on rainfall data to assess drought. Factors causing agricultural drought, such as precipitation, soil type and moisture, ground cover, and topography, among others, were very complex. All of these factors may have an impact on agriculture drought. Identifying drought solely based on rainfall had certain limitations. Thus, adopting drought index based on air temperature, soil moisture, and other factors (e.g., SPEI index, integrated meteorological drought index, and Palmer index),

or remote sensing methods to verify the results of the study, can improve the reliability of research results.

In the context of global climate change, future variations of China's arid climate and drought areas may become an urgent concern to policymakers. Adopting projected datasets of climate change under different future emission scenarios, and analyzing drought variations in China should be considered as topics for the next research program.

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