

RESEARCH ARTICLE

Dependence of 3-month Standardized Precipitation-Evapotranspiration Index dryness/wetness sensitivity on climatological precipitation over southwest China

Shanlei Sun¹  | Haishan Chen¹  | Jinjian Li² | Jiangfeng Wei^{1,3} | Guojie Wang⁴  | Ge Sun⁵ | Wenjian Hua¹  | Shujia Zhou¹ | Peng Deng¹

¹Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Key Laboratory of Meteorological Disaster, Ministry of Education/International Joint Research Laboratory on Climate and Environment Change, Nanjing University of Information Science and Technology (NUIST), Nanjing, China

²School of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu, China

³Jackson School of Geosciences, University of Texas at Austin, Austin, Texas

⁴School of Geography and Remote Sensing, Nanjing University of Information Science and Technology (NUIST), Nanjing, China

⁵Eastern Forest Environmental Threat Assessment Center, Southern Research Station, United States Department of Agriculture Forest Services, Raleigh, North Carolina

Correspondence

Shanlei Sun, International Joint Laboratory on Climate and Environment Change, Nanjing University of Information Science & Technology (NUIST), Ningliu Road 219, Nanjing 210044, China.
Email: ppsunsanlei@126.com

Funding information

National Natural Science Foundation of China, Grant/Award Number: 41605042 and 41625019; Natural Science Foundation of Jiangsu Province, China, Grant/Award Numbers: BK20151525, BK20160948 and BK20150922; Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions; Qinglan Project of Jiangsu Province, China.

In this study, we estimated the respective contributions of precipitation and reference evapotranspiration (ET_0) to annual SPEI-3 (3-month Standardized Precipitation-Evapotranspiration Index) anomalies over southwest China (SWC) using numerical experiments. Results show that the dominant factor (i.e., precipitation or ET_0) for the dryness/wetness anomalies during 1961–2012 existed due to inter-annual and inter-decadal changes over SWC, which indicates the underlying mechanisms of dry/wet conditions have changed. On the other hand, we calculate the dryness/wetness sensitivity to precipitation or ET_0 (defined as changes in SPEI-3 per millimetre) and find that the dryness/wetness sensitivity to ET_0 is higher than that to precipitation for the whole SWC and the overwhelming majority (99%) of the 269 sites. Overall, the above findings imply that the role of ET_0 in the dry/wet condition evolution is vital and should be paid more attentions. For the magnitude of the dryness/wetness sensitivity to precipitation or ET_0 , an evident increase from the southeast to northwest SWC is identified. Based on the analyses of the relationship between dryness/wetness sensitivity and climatological condition (i.e., precipitation, ET_0 , and aridity), the sensitivity magnitude is dependent on climatological precipitation and generally decreases with its increase. This study provides a wealth of quantitative information (e.g., dryness/wetness anomalies [sensitivity] caused by [to] precipitation and ET_0) for better understanding the underlying mechanisms of the dry/wet condition evolution.

KEYWORDS

dryness/wetness, reference evapotranspiration, sensitivity, separation method, southwest China

1 | INTRODUCTION

In response to the exacerbating climate change, the successive and rapid warming in particular (Intergovernmental Panel on Climate Change (IPCC), 2014), a growing number of evidences indicated that the dry/wet condition over the

mainland has varied but with evident regional differences and even the hydrological cycle at global scale has been accelerated during the past several decades (Oki and Kanae, 2006; Wild *et al.*, 2008; Dai, 2011; Sheffield *et al.*, 2012; McCabe and Wolock, 2013; Hamlington *et al.*, 2017). Specifically, drought characterized by below-normal water

availability over a period from several months to a few decades is an extreme case of dry/wet condition and regarded as the most damaging one of all the natural hazards (Wilhite, 2000); therefore, its changes (e.g., spatial extent, duration, and intensity), underlying mechanisms, monitoring and forecasting, and impacts have now become hot topics in the scientific community, for example, long-term droughts in the western North America (Schwalm *et al.*, 2012) and the north China (Cai *et al.*, 2015) and the recent short-term but severe droughts in California during 2011–2015 (AghaKouchak *et al.*, 2014; Diffenbaugh *et al.*, 2015; McEvoy *et al.*, 2015; Shukla *et al.*, 2015; Cheng *et al.*, 2016) and southwest China (SWC) in 2009/2010 (Barriopedro *et al.*, 2012; Feng *et al.*, 2014; Zhang *et al.*, 2014; Wang *et al.*, 2015). In brief, analysing dryness/wetness variations will benefit for water resources management and planning, agriculture production, and ecosystem services (Sun *et al.*, 2015).

Because of the lack of sufficient long-term and continuous measurements (e.g., soil moisture, lake level, and streamflow), it is difficult to directly conduct dryness/wetness and drought analyses and attributions at regional scales (Peng *et al.*, 2015; 2017; Yin *et al.*, 2015a; 2015b; Cheng *et al.*, 2016; Liu *et al.*, 2017a). To overcome this difficulty, various indices are developed to represent dryness/wetness and drought (Palmer, 1965; McKee *et al.*, 1993; Vicente-Serrano *et al.*, 2012). They are mainly derived from precipitation and/or reference evapotranspiration (ET_0) which is estimated from the Thornthwaite (Thornthwaite, 1948) or the Food and Agricultural Organization (FAO) Penman–Monteith approach (Allen *et al.*, 1998). In general, these indices have been widely evidenced to be good proxies to identify dry/wet conditions over the world (Dai, 2011; Vicente-Serrano *et al.*, 2012) and then extensively used to assess climate change impacts on regional and global dryness/wetness and drought (Wang and Chen, 2012; Trenberth *et al.*, 2013; Sun *et al.*, 2015; 2016; 2017b; Vicente-Serrano *et al.*, 2015). Essentially, dry/wet condition for a certain region is an issue of water balance (Hobbins *et al.*, 2008) and consequently is closely associated with water supply (e.g., precipitation; Williams *et al.*, 2015). Despite that, investigations about precipitation changes alone are insufficient for understanding dryness/wetness fluctuations (Shukla *et al.*, 2015), especially in the context of a warming climate. It is well known that evapotranspiration (an important component of water demand) or ET_0 (refers to the atmospheric evaporative demand) negatively correlates with the terrestrial water budget (Hobbins *et al.*, 2008), that is, its increase tends to reduce water availability and vice versa. As a result, the spatio-temporal variability of evapotranspiration or ET_0 is also essential in analysing dryness/wetness and drought changes (Blackie and Simpson, 1993). Recently, a wealth of studies have evidenced the effects on evolutions of dry/wet condition and drought (Hu and Willson, 2000; Diffenbaugh

et al., 2015; Shukla *et al.*, 2015; Vicente-Serrano *et al.*, 2015; Williams *et al.*, 2015; Sun *et al.*, 2016; 2017b). For instance, Williams *et al.* (2015) pointed out that although precipitation was the determinant factor of drought over California, impacts of increasing evapotranspiration induced by anthropogenic warming could not be neglected in 2012–2014. Sun *et al.* (2016) reported that contribution of ET_0 to annual SWC SPEI-3 (3-month Standardized Precipitation-Evapotranspiration Index) trend was comparable to that of precipitation during 1961–2012.

Despite that the previous studies revealed precipitation and ET_0 impacts on dryness/wetness variation and different drought events, there still exists a question to be solved: What magnitude of dryness/wetness is changed by precipitation or ET_0 variation per millimetre (i.e., dryness/wetness sensitivity in this study)? This sensitivity is useful for a better and in-depth understanding of the respective roles of precipitation and ET_0 in dry/wet processes and even drought. Regarding to this issue, a limited number of studies have been conducted by designing numerical experiments with several drought indices (e.g., Vicente-Serrano *et al.*, 2015; Zhang *et al.*, 2016b). For example, Vicente-Serrano *et al.* (2015) reconstructed the long-term precipitation and ET_0 series from simulations with varying means and variances as the inputs of different drought indices, and evaluated dryness/wetness sensitivity at the global scale. Based on Palmer drought severity index (PDSI) and several numerical experiments, Zhang *et al.* (2016b) analysed dryness/wetness response to precipitation and ET_0 changes over China. Nevertheless, a shortage should be noted in quantifying the sensitivity magnitude in the above studies. Specifically, these experiments are performed using the original data (i.e., including monthly and annual variations) for some one input and the processed data (e.g., eliminating monthly variation and/or annual trend) for the others; then, the difference between the control simulation (i.e., for each input including monthly and annual variations) and a certain sensitivity experiment is believed to be the drought sensitivity to the selected variable. It is not difficult to find that these methods of sensitivity analyses have not comprehensively considered the effects of interactions between the influential variables (e.g., precipitation and ET_0) on dryness/wetness (Zhang *et al.*, 2013; Liu *et al.*, 2016), consequently biasing the estimated sensitivity magnitude from the actual value.

During the past several decades, dry/wet condition has obviously changed across China, but the variations differ from region to region (Liu *et al.*, 2012; Yu *et al.*, 2014; Zhang *et al.*, 2016a; 2016b). For example, northwest part has become wetter; however, drying and intensifying droughts (e.g., higher insensitive and larger extent) have occurred over SWC, especially since the start of 21st century (Yang *et al.*, 2012a; Yu *et al.*, 2014; Sun *et al.*, 2016; 2017b). In particular, a severe drought prolonging from autumn of 2009 to spring of 2010 over SWC was believed

to be a record-breaking event from perspective of the historical meteorological observations, and caused approximately 21 million people being short of drinking water and economic losses nearly \$30 billion (Yang *et al.*, 2012a; Lu *et al.*, 2014). On the other hand, numerous observational analyses suggested that precipitation and ET_0 -related climate elements (i.e., temperature, relative humidity, sunshine duration, and wind speed) have significantly changed in SWC (Qin *et al.*, 2010; Li *et al.*, 2011; 2012; Yang *et al.*, 2012b; Zeng *et al.*, 2016), which finally exert impacts on dry/wet condition. As such, more and more efforts have been devoted to exploring the underlying mechanisms of dryness/wetness and droughts changes in this region (Barriopedro *et al.*, 2012; Wang and Chen, 2012; Feng *et al.*, 2014; Zhang *et al.*, 2014; Wang *et al.*, 2015; Sun *et al.*, 2016; 2017b; Liu *et al.*, 2017b). Feng *et al.* (2014) stated that the severe SWC droughts during 1951–2010 were closely associated with the circulation anomalies induced by remote forcing from the tropical Pacific and North Atlantic Oceans. Through quantifying respective contribution of precipitation and ET_0 to SPEI-3 dryness/wetness trends for the whole SWC, Sun *et al.* (2016) reported that the drying during 1961–2012 and the wetting during 1976–1995 could be attributed to the declining precipitation and ET_0 , respectively. In short, these studies provided critical references for knowing SWC dry/wet condition and even drought variations in response to climate change from different perspectives. Nevertheless, the dryness/wetness sensitivity to precipitation and ET_0 in this region are scarcely investigated to date, which can support more complete theoretical knowledge for understanding SWC dry/wet condition evolutions, and monitoring and forecasting drought. Thus, the major aims of the current study are as follows: (a) to separate the respective contributions of precipitation and ET_0 to annual dryness/wetness anomalies during 1961–2012 using a new separation method (Sun *et al.*, 2014; 2017a), which can successfully eliminated the effects of interactions and thus (b) to identify whether there are obvious differences in dryness/wetness sensitivity to precipitation and ET_0 at site scale and try to explain the possible differences from climatological perspective.

2 | DATA AND METHODOLOGY

2.1 | Study area and data

In this study, we specify the study region of SWC between 21 and 34°N and 97 and 110°E, which mainly includes Sichuan, Guizhou, and Yunnan provinces, and Chongqing municipality, as well as west Guangxi Autonomous Region (Figure 1). SWC covers a large geographic area, basically characterized by declining in elevation from northwest to southeast. In general, SWC belongs to a typical subtropical monsoonal climate, with annual precipitation (ET_0) of 1098.42 mm (989.65 mm). Besides, precipitation (Figure 2;

ET_0) shows a distinct seasonality and have a (two) peak(s) occurring in July (May and July). To perform comprehensive analyses, routine meteorological measurements are required. As a result, a monthly meteorological dataset including precipitation (mm), mean, maximum, and minimum air temperatures at 2-m height (°C), wind speed at 10-m height (m/s), sunshine duration (hr/month), and relative humidity (%) is collected from China Meteorological Administration (CMA). This dataset spans 1960–2012 and is observed at 334 sites over SWC. Before using, it should be noted that the historical observations potentially exist two data quality issues, that is, inhomogeneity caused by non-climatic factors (e.g., changes in instruments, observing practices, station locations, statistical methods, and station environment), and missing values due to the observer's fault and the instrument failure. The more detailed information to process the data quality issues can be found in Sun *et al.* (2016). Lastly, data of 269 sites are remained (Figure 1).

2.2 | Penman–Monteith equation and standardized precipitation-evapotranspiration index

Sheffield *et al.* (2012) stated that the use of physically realistic ET_0 formulation (e.g., the FAO Penman–Monteith equation) with the wealth of in situ data sources is favourable for better estimates of drought variations and its relationship with climate change. Therefore, Penman–Monteith equation is used in this study (Allen *et al.*, 1998; Katerji and Rana, 2011). It reads

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \frac{900}{T_{ave} + 273} \cdot Wnd \cdot Vpd}{\Delta + \gamma \cdot (1 + 0.34 \cdot Wnd)}, \quad (1)$$

where Rn ($MJ\ m^{-2}\ day^{-1}$) represents net radiation (detailed computations in Appendix S1, Supporting Information); G ($MJ\ m^{-2}\ day^{-1}$) is soil heat flux density and is usually set as 0 at longer (e.g., monthly) scale; γ ($kPa/^\circ C$) and Δ ($kPa/^\circ C$) are the psychrometric constant and the slope vapour pressure curve, respectively; Wnd (m/s) denotes wind speed at 2-m height, which can be derived from wind speed at 10-m height; Vpd (kPa) is the difference between saturation and actual vapour pressure, named as vapour pressure deficit; and T_{ave} ($^\circ C$) represents mean temperature. For more description about these variables, please see Allen *et al.* (1998). Notably, the computation of ET_0 is conducted on monthly scale, and then annual value can be obtained as the sum of monthly ET_0 within a certain year.

By comparing against drought statistics from various yearbooks of meteorological disasters, Wang and Chen (2012) concluded that standardized precipitation-evapotranspiration index (SPEI) can well capture the major characteristics of drought in SWC. Therefore, this index is employed in the present study. Based on concept of the standardized precipitation index (SPI; McKee *et al.*, 1993), Vicente-Serrano *et al.* (2010) first proposed SPEI with the inputs of monthly precipitation and ET_0 . Subsequently, it

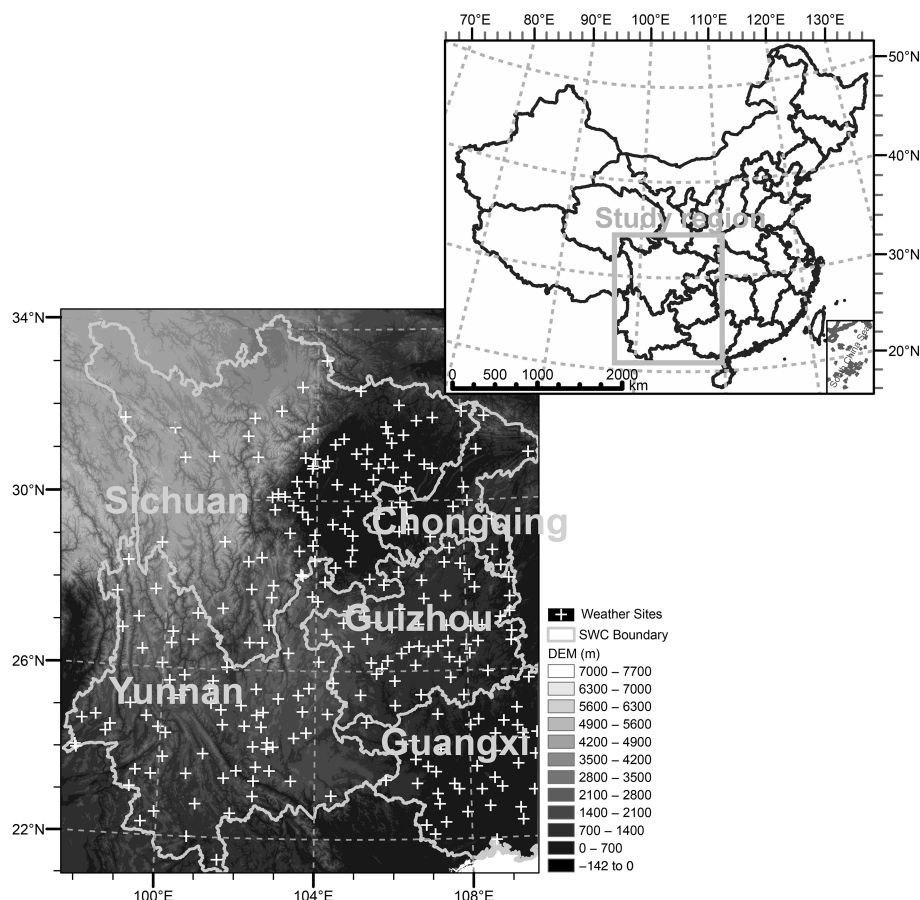


FIGURE 1 Location of SWC with 269 weather sites. The shading denotes the elevation, which is represented using digital elevation model (DEM) with a spatial resolution of 90×90 m. This data can be obtained from <http://srtm.csi.cgiar.org/>

has been widely used for various researches about drought and dryness/wetness over the globe (Wang and Chen, 2012; Beguería *et al.*, 2014; Hernandez and Uddameri, 2014; Xu *et al.*, 2015), because SPEI is easy to compute and can flexibly capture dry/wet events on different timescales (e.g., 1, 3, 6, and 12 months). Usually, for a given region, negative and positive SPEI implies dry and wet, respectively. Here, we select the SPEI-3 for representing dry/wet conditions in SWC, and obtain annual SPEI-3 by averaging monthly values with a certain year. About the detailed principles of

the SPEI model, the reader can read Vicente-Serrano *et al.* (2010).

2.3 | Quantifying the respective contributions of precipitation and ET_0 to annual SPEI-3 anomalies

Considering that the interactions among driving factors can introduce some uncertainties into the separated contributions of each factor alone to the object climate variable, Sun *et al.* (2014; 2017a) develop a new separation method for eliminating the confound effect. This method has been successfully applied in attributing changes of hydrological variables (i.e., streamflow and evapotranspiration) in Poyang Lake Basin, China (Sun *et al.*, 2014) and ET_0 in SWC (Sun *et al.*, 2017a) to different driving factors, with a higher accuracy and efficiency. Therefore, we quantify the respective contributions of precipitation and ET_0 to annual SPEI-3 anomalies based on the concept of this new separation method. For this method, a fundamental hypothesis is that annual anomalous SPEI-3 is jointly caused by anomalies of all the driving factors, and thus equals to their linearly accumulative contributions. Overall, this method includes two procedures:

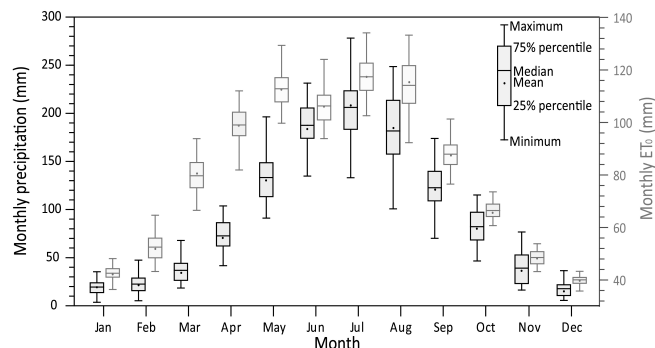


FIGURE 2 Monthly precipitation and ET_0 averaged over SWC from 1961 to 2012

- *Appropriate numerical experiments* (Table 1). In the current study, six experiments are designed (Table 1) and

conducted using the SPEI model, that is, one control (SPEI_CTL) and one sensitivity experiment (SPEI_*i*; *i* refers to precipitation, *Rn*, *Tave*, *Wnd*, and *Vpd*) for each driving factor. Notably, the inputs of the SPEI model differ among these experiments. The SPEI_CTL is run with original data of the five factors from 1960–2012. However, the SPEI_*i* sensitivity experiment repeatedly employs 52-year (1961–2012) mean monthly values of *i* factor, but uses original data for the other four factors from 1960 to 2012 as inputs for estimating monthly SPEI-3. For each experiment, the corresponding annual SPEI-3 anomalies can be calculated through subtracting its 52-year mean.

- *Efficient algorithm for obtaining contributions of each factor alone.* According to the concept of the separation equations by Sun *et al.* (2014; 2017a), we hypothesize that the SPEI-3 anomalies of the SPEI_*i* sensitivity experiment are induced by the driving factors except for *i*. For example, the SPEI_PRE SPEI-3 anomalies are due to anomalous *Rn*, *Tave*, *Wnd*, and *Vpd*. Therefore, new formulation for the contributions of each factor alone (C_i) to annual SPEI-3 anomalies can be expressed as

$$\sum_{k \neq i}^n C_{k,j} = V_{\text{SPEI}_i,j} \quad (2)$$

where $\sum_{k \neq i}^n C_{k,j}$ represents the accumulative contributions of all the driving factors (except for *i* factor) to annual SPEI-3 anomalies at *j*th year; *n* equals to 5 here, indicating the number of sensitivity experiments; and $V_{\text{SPEI}_i,j}$ represents annual SPEI-3 anomalies at *j*th year induced by the driving factors except for *i*.

To solve the above equations, one factor's contributions to annual SPEI-3 anomalies can be obtained by

$$C_{i,j} = \frac{\sum_{k \neq i}^n V_{\text{SPEI}_k,j} - (n-2) \cdot V_{\text{SPEI}_i,j}}{n-1} \quad (3)$$

This approach will be conducted at each site and each year. Please note that the ET_0 contributions to annual SPEI-

3 anomalies are the sum of the respective contributions of *Rn*, *Tave*, *Vpd*, and *Wnd*.

3 | RESULTS

3.1 | Contributions of precipitation and ET_0 to dryness/wetness anomalies

To have a basic knowledge of recent changes in climate background and dryness/wetness over SWC, we first show the time series of annual precipitation, ET_0 , and SPEI-3 anomalies during 1961–2012 (Figure 3a). It can be seen that the annual precipitation anomalies are mostly positive before 2000s (especially for the period after 1990) and generally negative afterward (the minimum of −188.5 mm in 2011). However, compared to the multi-year mean, the annual ET_0 is basically higher before 1980s and after 2000s, but lower between these two periods. Under the joint impacts of precipitation and ET_0 , annual SPEI-3 is positive (wetter) in most years before 2000s, and negative (drier) after then. Generally, the variations of SPEI-3 are strongly associated with those of precipitation and ET_0 (inter-annual correlation = 0.79 and −0.73 with $p < .01$, respectively), implying that SPEI-3 declines with decreased precipitation and increased ET_0 , and vice versa. Therefore, the combined effects of precipitation (negative anomalies) and ET_0 (positive anomalies) may be responsible for a significant increase in extreme drought over SWC since the start of 21st century (Barriopedro *et al.*, 2012; Feng *et al.*, 2014; Zhang *et al.*, 2014; Wang *et al.*, 2015; Sun *et al.*, 2016).

To quantitatively analyse the role of precipitation and ET_0 in SPEI-3, we have improved the separation method of Sun *et al.* (2014; 2017a), which was originally designed for attributing hydrological components (e.g., streamflow and evapotranspiration) and ET_0 trends to climate change, and then employed it to estimate precipitation and ET_0 contributions to SPEI-3 anomalies in each year. Comparing the cumulative contributions of precipitation and ET_0 against the SPEI_CTL SPEI-3 anomalies at each site (Figure S1), we find that the regression coefficients are between 0.977 and 1.092 (Figure S1a), and meanwhile all the sites exhibit a correlation coefficient (*R*) higher than 0.99 ($p < .01$; Figure S1b). These suggest that this new method is efficient to isolate the contributions of precipitation and ET_0 to anomalous SPEI-3. Figure 3b shows the respective contributions of regional mean precipitation and ET_0 over SWC. Overall, the dominant factor for anomalous SPEI-3 (namely dryness/wetness) varies from year to year. Before 1980s, negative SPEI-3 anomalies are mainly due to the positive ET_0 anomalies, while positive SPEI-3 anomalies are mainly caused by the positive precipitation anomalies. In the 1980s, precipitation anomalies determine SPEI-3 anomalies in most years, including 1983–1985 and 1986–1990. Except for the slightly negative SPEI-3 anomalies in 1994, there remain positive

TABLE 1 Detailed information about the experiments

Experiments	Description
SPEI_CTL	Monthly precipitation, <i>Rn</i> , <i>Tave</i> , <i>Wnd</i> , and <i>Vpd</i> during 1960–2012
SPEI_PRE	Monthly precipitation fixed at 52-year (1961–2012) mean; monthly <i>Rn</i> , <i>Tave</i> , <i>Wnd</i> , and <i>Vpd</i> during 1960–2012
SPEI_RN	Monthly <i>Rn</i> fixed at 52-year monthly mean; monthly precipitation, <i>Tave</i> , <i>Wnd</i> , and <i>Vpd</i> during 1960–2012
SPEI_TAVE	Monthly <i>Tave</i> fixed at 52-year monthly mean; monthly <i>Rn</i> , precipitation, <i>Wnd</i> and <i>Vpd</i> during 1960–2012
SPEI_WND	Monthly <i>Wnd</i> fixed at 52-year monthly mean; monthly <i>Rn</i> , <i>Tave</i> , precipitation and <i>Vpd</i> during 1960–2012
SPEI_VPD	Monthly <i>Vpd</i> fixed at 52-year monthly mean; monthly <i>Rn</i> , <i>Tave</i> , <i>Wnd</i> , and precipitation during 1960–2012

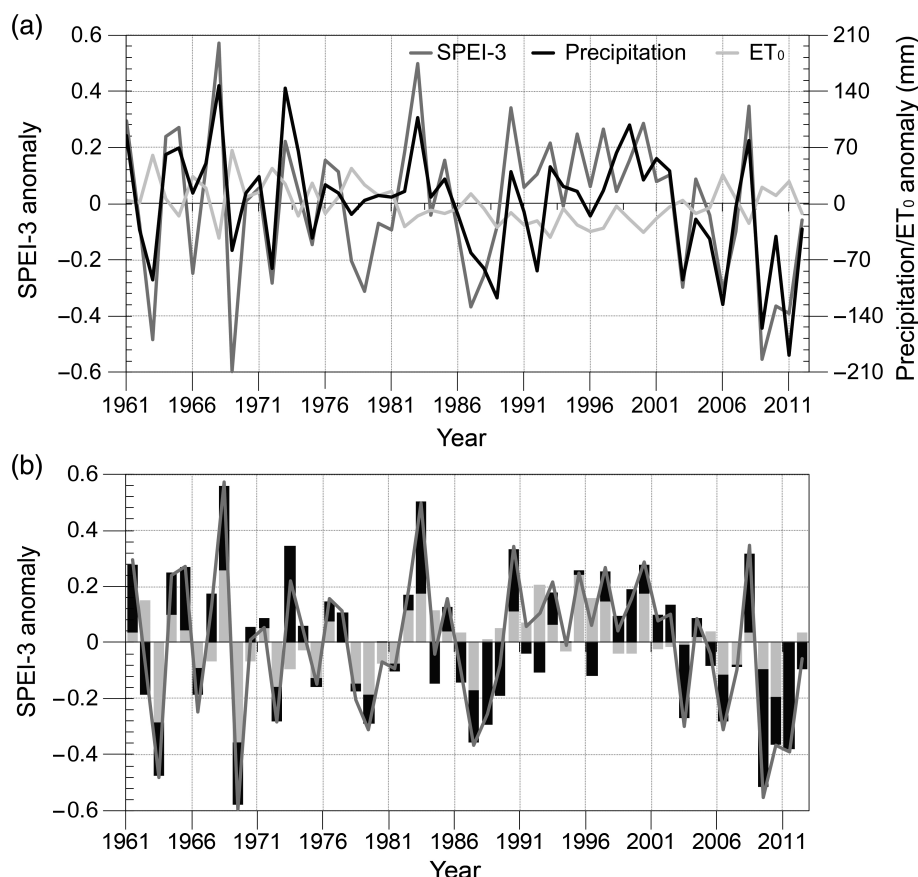


FIGURE 3 (a) SWC regional mean anomalies of SPEI-3, precipitation and ET₀. (b) Precipitation and ET₀ contributions to SPEI-3 anomalies

SPEI-3 anomalies in 1990s over SWC, which are generally attributed to the negative ET₀ anomalies. Since 2000, SPEI-3 is basically negative, especially after 2007, indicating that SWC is drier in this period. It is apparent that decreases in precipitation should be responsible for declined SPEI-3 after 2000. All in all, these findings suggest that dryness/wetness over SWC and the underlying mechanisms have changed during 1961–2012, and ET₀ can play a comparable role to precipitation in affecting the dry/wet condition. This basically agrees well with our previous conclusions about ET₀ and precipitation influences in decadal drought anomalies (Sun *et al.*, 2017b) and other results (AghaKouchak *et al.*, 2014; Shukla *et al.*, 2015; Williams *et al.*, 2015; Zhang *et al.*, 2016b).

3.2 | Sensitivity of dryness/wetness to precipitation and ET₀

Based on the improved separation method, we have estimated the contributions of precipitation and ET₀ alone to the SWC regional mean SPEI-3 anomalies. This provides a necessary and reliable way to investigate SPEI-3 sensitivity to precipitation and ET₀; this method can remove the impacts of interactions between precipitation and ET₀ on SPEI-3 anomalies, which can influence the sensitivity magnitudes and thus cause some uncertainties for the conclusions (Zhang *et al.*, 2013; Liu *et al.*, 2016). Therefore,

SPEI-3 sensitivity to precipitation (S_{pre} , ET_0 , S_{et0}) is defined as the slope of a linear regression with the 52-year sample, which has the separated precipitation (ET₀) contributions as the dependent variable and precipitation (ET₀) anomalies as the independent variable. Figure 4a,b shows the scatterplots of the separated precipitation and ET₀ contributions against precipitation and ET₀ anomalies, respectively. Obviously, precipitation (ET₀) anomalies with the corresponding separated contributions ($R = 0.92$, $p < .01$; -0.83 , $p < .01$) exhibit a higher correlation than those with SPEI-3 anomalies ($R = 0.79$, $p < .01$ in Figure S2a; -0.73 , $p < .01$ in Figure S2b). As seen in Figure 4a,b, S_{pre} and S_{et0} are positive and negative, respectively. This is consistent with the common knowledge. In addition, comparing Figure 4a against Figure S2a and Figure 4b against Figure S2b, the samples in Figure 4 are closer to the fitting lines than those in Figure S2. The above analyses imply that, at least partly, the new separation method improves the accuracy of the estimated contributions of each influential factor to SPEI-3. For the whole SWC, the magnitude of S_{et0} (0.0042 mm) is nearly double of that of S_{pre} (0.0023 mm), suggesting that ET₀ is more important in controlling the SWC dryness/wetness condition even if it has the same variations as precipitation.

The same analysis framework and numerical experiments for quantifying precipitation and ET₀ contributions are applied to the 269 weather sites. S_{pre} and S_{et0} at each site

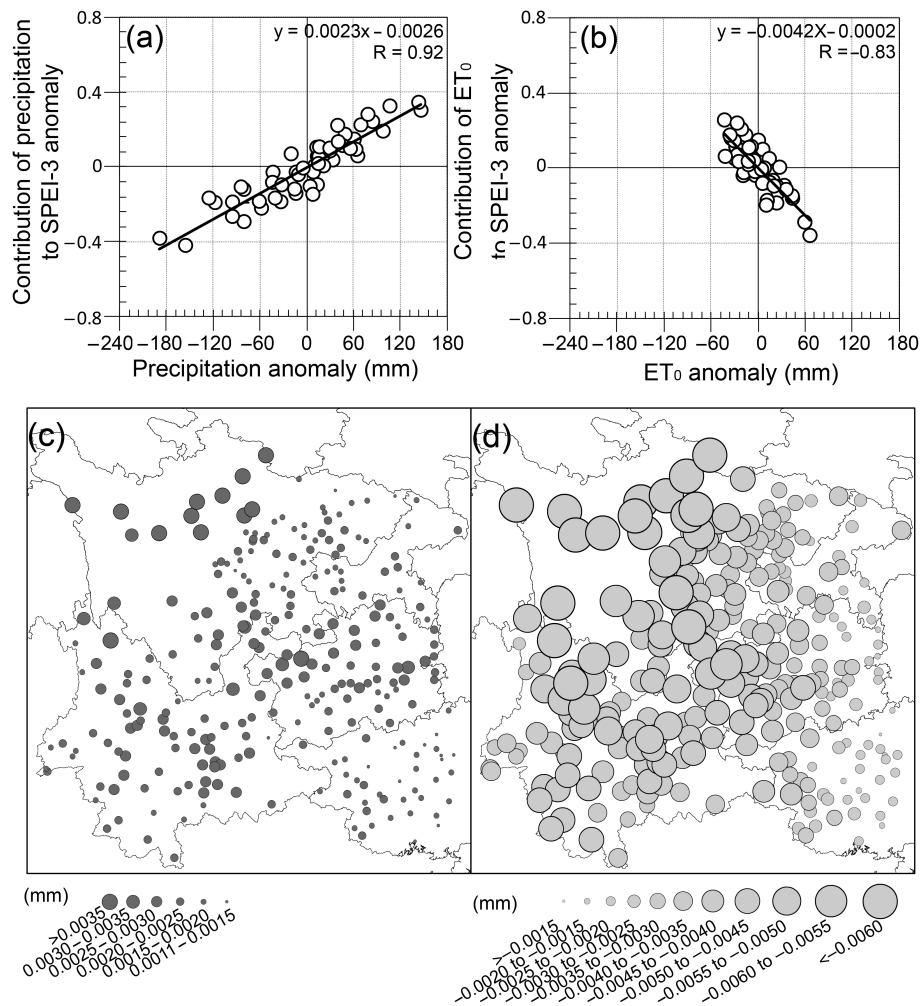


FIGURE 4 Scatterplots of (a) precipitation contributions versus precipitation anomalies, (b) ET₀ contributions versus ET₀ anomalies, and SPEI-3 sensitivity to (c) precipitation and (d) ET₀. In (a, b), R is significant with $p < .01$

are shown in Figure 4c,d, respectively. Generally, S_{pre} exhibits a spatial pattern with higher values (>0.0030 mm) in the northwest and the lower ones (<0.0020 mm) in the southeast SWC. At the overwhelming majority of sites, S_{pre} is between 0.0015 and 0.0030 mm. For the magnitude of S_{et0} , it shows a clear spatial distribution characterized by an increase from the southeast to the northwest. We also compare the magnitude of S_{pre} against that of S_{et0} for each site, and find that S_{et0} is stronger at 99% of the 269 sites.

3.3 | Impact of climatological condition on dryness/wetness sensitivity

Why there are evident spatial differences in S_{pre} and S_{et0} (Figure 4), and what should be the possible cause? Vicente-Serrano *et al.* (2015) and Gudmundsson and Seneviratne (2016) pointed out that the spatial variations of dryness/wetness sensitivity to climate change are closely associated with the climatological condition (e.g., aridity; referred as a ratio of ET₀ divided by precipitation). Therefore, we hypothesize that the divergences in the sensitivity are dependent on climatological condition, and checked the relationships of S_{pre}

or S_{et0} with climatological precipitation (P_{cli}), ET₀ (ET_{0cli}), and aridity (A_{cli}). The results are shown in Figure 5. Both S_{pre} and S_{et0} are strongly correlated with P_{cli} (Figure 5a for S_{pre} and Figure 5b for S_{et0}) and A_{cli} (Figure 5e for S_{pre} and Figure 5f for S_{et0}). In general, the magnitudes of S_{pre} and S_{et0} decrease dramatically with increasing P_{cli} (A_{cli}), indicating that where there is higher P_{cli} (or A_{cli}), the sensitivity magnitude is lower. To quantify the changes of S_{pre} (S_{et0}) associated with climatological conditions, two different regression lines (i.e., linear and logarithmic) are included. From the perspective of R , the logarithmic function works best with R of -0.74 ($p < .01$; 0.73 , $p < .01$), -0.05 ($p < .01$; 0.03 , $p < .01$) and -0.62 ($p < .01$; 0.62 , $p < .01$) between S_{pre} (S_{et0}) and P_{cli} , ET_{0cli} , and A_{cli} , respectively. However, the relationship between S_{pre} (Figure 5c; S_{et0} in Figure 5d) and ET_{0cli} is very weak despite of the significant ($p < .01$) correlation. Therefore, ET_{0cli} has very limited impacts on S_{pre} and S_{et0} , and the spatial differences in S_{pre} (S_{et0}) are potentially controlled by P_{cli} or A_{cli} . The higher R and the lower root-mean-square error (RMSE) suggest that the relationships between S_{pre} or S_{et0} and P_{cli} are a little stronger than that to A_{cli} . This might be mainly

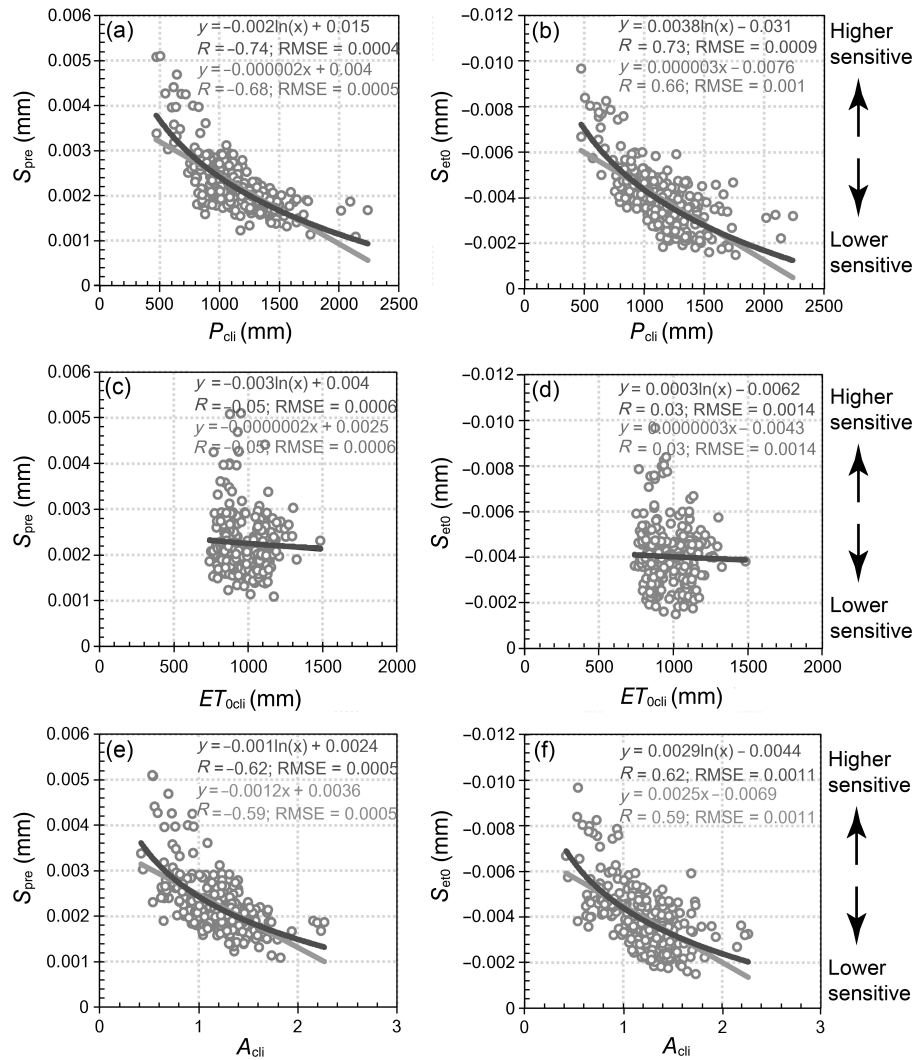


FIGURE 5 Scatterplots of S_{pre} versus (a) P_{cli} , (c) ET_{0cli} , and (e) A_{cli} ; and S_{et0} versus (b) P_{cli} , (d) ET_{0cli} , and (f) A_{cli} over SWC. For each figure, R is significant with $p < .01$

because of the aridity algorithm includes ET_0 (reflected by a lower relationship of ET_0 with S_{pre} or S_{et0}), consequently reducing the robustness of the regressions. A multi-linear regression with stepwise algorithm [S_{pre} (S_{et0}) as dependent variable, but the logarithms of P_{cli} and A_{cli} as independent variables] is established, and the results show that A_{cli} is excluded [$p = 0.13$ (0.33) for the S_{pre} (S_{et0}) regression] because of the high collinearity between A_{cli} and P_{cli} . Besides, the correlation analyses show that R between P_{cli} and A_{cli} is 0.87 ($p < .01$). These indicates that the dependence of A_{cli} on S_{pre} (S_{et0}) can be ultimately attributed to P_{cli} , and therefore we conclude that S_{pre} (S_{et0}) over SWC logarithmically depends on P_{cli} with a formulation of $S_{pre} = -0.002 \times \ln(P_{cli}) + 0.015$ [$S_{et0} = 0.0038 \times \ln(P_{cli}) - 0.031$].

4 | DISCUSSION AND CONCLUSION

For the whole SWC, the dryness/wetness anomalies are mostly positive before 2000s and negative afterwards. In order to quantitatively explain the SPEI-3 anomalies, a new

separation method is improved and shows a good performance in separating the respective contributions of precipitation and ET_0 at the whole SWC and site scales. Despite of precipitation with a predominant impact on SPEI-3 anomalies, ET_0 can have comparable or higher contributions in some years (e.g., before 1980s and in 1990s), which indicates that ET_0 played an important role in dryness/wetness processes in SWC. For dryness/wetness sensitivity to precipitation and ET_0 , the SPEI-3 is more sensitive to ET_0 over SWC and at 99% of the 269 sites. Additionally, there are evident spatial differences in sensitivity, with an increase from the southeast to the northwest SWC. By analysing the relationship of dryness/wetness sensitivity with climatological condition (i.e., precipitation, ET_0 , and aridity), we conclude that the sensitivity is mainly controlled by climatological precipitation and generally decreases with its increase.

Our findings suggest that the sensitivity of SPEI-3 dryness/wetness to ET_0 is stronger than to precipitation over SWC, which is seemingly opposite to our common

knowledge. In this study, we define S_{pre} as a change with total precipitation, but only part of the precipitation directly affects soil moisture (called effective precipitation) and rest goes to evaporation and runoff. The effective precipitation is less than the total precipitation (Wen and Liu, 1995; Crockford and Richardson, 2000; Fan *et al.*, 2007; Wei *et al.*, 2008), which may play a role in the sensitivity. Additionally, the other possible reason is the much larger variability of precipitation compared with that of ET_0 (Figures 3a and 4a, b; standard deviation of 70.46 mm vs. 24.44 mm). Although S_{pre} is smaller, it does not indicate a smaller contribution of precipitation to SPEI-3 anomalies (Figure 3b), which is also dependent on the magnitude of precipitation anomaly. In addition, several limitations of this study should be kept in mind. Only a widely used drought index (i.e., SPEI) is employed in this study, which potentially influences the final results (e.g., a logarithmic relationship between SPEI-3 sensitivity and climatological condition identified here); therefore, whether types of the functional relationship of SPEI-3 sensitivity with climatological condition differ among various drought indices should be further investigated in the future. Considering the complex associations of SPEI-3 with precipitation and ET_0 , the separated contributions by linear equations (i.e., Equation (3)) may introduce some uncertainties into our results, in spite of a better performance in quantifying the irrespective impacts of precipitation and ET_0 on SPEI-3 anomalies (shown in section 3.1). The definition of SPEI-3 sensitivity to precipitation and ET_0 based on a linear hypothesis can also somewhat influence the results. Anyway, our results are encouraging and can provide a wealth of quantitative information for better understanding the physical mechanisms of dry/wet condition evolution; furthermore, the higher dryness/wetness sensitivity to ET_0 than to precipitation is detected in this study, which highlights that ET_0 role in dryness/wetness changes should be paid enough attention to improve the monitoring and forecasting level of droughts (McEvoy *et al.*, 2015; Sun *et al.*, 2017b). Meanwhile, this information can help for planning water resources and making the corresponding measure to reduce the negative influences of climate change-induced droughts in SWC. It should be noted that this study focuses on the dependence of annual SPEI-3 sensitivity. However, for comprehensively understanding dry/wet condition evolutions, to investigate on monthly SPEI-3 sensitivity (e.g., whether monthly differences exist and the possible causes) is also necessary and important; thus, more efforts should be devoted on this issue in the future researches.

ACKNOWLEDGEMENTS

This work was jointly supported by National Natural Science Foundation of China (Grant Nos. 41605042 and 41625019), Natural Science Foundation of Jiangsu Province, China (Grant Nos. BK20151525, BK20160948 and

BK20150922), Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions, and Qinglan Project of Jiangsu Province, China. The source code for the model used in this study and input files necessary to reproduce the numerical experiments are available from the authors upon request (ppsunsanlei@126.com). The meteorological observations at the 334 weather sites are from China Meteorological Administration (CMA).

ORCID

Shanlei Sun  <http://orcid.org/0000-0002-7237-2722>

Haishan Chen  <http://orcid.org/0000-0002-2403-3187>

Guojie Wang  <http://orcid.org/0000-0001-5899-1773>

Wenjian Hua  <http://orcid.org/0000-0002-9705-3234>

REFERENCES

- AghaKouchak, A., Cheng, L., Omid, M. and Alireza, F. (2014) Global warming and changes in risk of concurrent climate extremes: insights from the 2014 California drought. *Geophysical Research Letters*, 41(24), 8847–8852.
- Allen, R., Pereira, L., Raes, D. and Smith, M. (1998) *Crop Evapotranspiration Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization of the United Nations.
- Barriopedro, D., Gouveia, C.M., Trigo, R.M. and Wang, L. (2012) The 2009/10 drought in China: possible causes and impacts on vegetation. *Journal of Hydrometeorology*, 13, 1251–1267.
- Beguería, S., Vicente-Serrano, S.M., Reig, F. and Latorre, B. (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, 34, 3001–3023.
- Blackie, J.R. and Simpson, T.K.M. (1993) Climatic variability within the Balquhider catchments and its effect on Penman potential evaporation. *Journal of Hydrology*, 145, 371–387.
- Cai, Q., Liu, Y., Liu, H. and Ren, J. (2015) Reconstruction of drought variability in north China and its association with sea surface temperature in the joining area of Asia and Indian–Pacific Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 417, 554–560.
- Cheng, L., Hoerling, M., Aghakouchak, A., Livneh, B., Quan, X.W. and Eischeid, J. (2016) How has human-induced climate change affected California drought risk. *Journal of Climate*, 29, 111–120.
- Crockford, R.H. and Richardson, D.P. (2000) Partitioning of rainfall into throughfall, streamflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes*, 14, 2903–2920.
- Dai, A. (2011) Characteristics and trends in various forms of the Palmer drought severity index during 1900–2008. *Journal of Geophysical Research*, 116, D12115. <https://doi.org/10.1029/2010JD015541>.
- Diffenbaugh, N.S., Swain, D.L. and Touma, D. (2015) Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, 112(13), 3931–3936.
- Fan, S., Gao, Y., Cheng, Y. and Bai, Q. (2007) Rainfall-intercepting capability of forest canopy. *Scientia Geographica Sinica*, 27, 200–204 (in Chinese with English Abstract).
- Feng, L., Li, T. and Yu, W. (2014) Cause of severe droughts in southwest China during 1951–2010. *Climate Dynamics*, 43, 2033–2042.
- Gudmundsson, L.G.P. and Seneviratne, S.I. (2016) The sensitivity of water availability to changes in the aridity index and other factors—a probabilistic analysis in the Budyko space. *Geophysical Research Letters*, 43, 6985–6994.
- Hamlington, B.D., Reager, J.T., Lo, M.H., Karnauskas, K.B. and Leben, R.R. (2017) Separating decadal global water cycle variability from sea level rise. *Scientific Reports*, 7, 995. <https://doi.org/10.1038/s41598-017-00875-5>.
- Hernandez, E.A. and Uddameri, V. (2014) Standardized precipitation evaporation index (SPEI)-based drought assessment in semi-arid south Texas. *Environmental Earth Sciences*, 71, 2491–2501.
- Hobbins, M.T., Dai, A., Roderick, M.L. and Farquhar, G.D. (2008) Revisiting the parameterization of potential evaporation as a driver of long-term water

- balance trends. *Geophysical Research Letters*, 35, L12403. <https://doi.org/10.1029/2008GL033840>.
- Hu, Q. and Willson, G.D. (2000) Effect of temperature anomalies on the Palmer drought severity index in the central United States. *International Journal of Climatology*, 20, 1899–1911.
- Intergovernmental Panel on Climate Change (IPCC). (2014) Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R. C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 1–32.
- Katerji, N. and Rana, G. (2011) Crop reference evapotranspiration: a discussion of the concept, analysis of the process and validation. *Water Resources Management*, 25(6), 1581–1600.
- Li, Z., He, Y., An, W., Song, L., Zhang, W., Catto, N., Wang, Y., Wang, S., Liu, H., Cao, W., Theakstone, W.H., Wang, S. and Du, J. (2011) Climate and glacier change in southwestern China during the past several decades. *Environmental Research Letters*, 6, 04540. <https://doi.org/10.1088/1748-9326/6/4/045404>.
- Li, Z., Feng, Q., Zhang, W., He, Y., Wang, X., Catto, N., An, W., Du, J., Chen, A., Liu, L. and Hu, M. (2012) Decreasing trend of sunshine hours and related driving forces in southwestern China. *Theoretical and Applied Climatology*, 109, 305–321.
- Liu, X., Li, D. and Wang, J. (2012) Spatiotemporal characteristics of drought over China during 1961–2009. *Journal of Desert Research*, 32(2), 473–483 (in Chinese with English abstract).
- Liu, T., Li, L., Lai, J., Liu, C. and Zhuang, W. (2016) Reference evapotranspiration change and its sensitivity to climate variables in southwest China. *Theoretical and Applied Climatology*, 125(3), 499–508.
- Liu, X.M., Yang, T.T., Hsu, K., Liu, C.M. and Sorooshian, S. (2017a) Evaluating the streamflow simulation capability of PERSIANN-CDR daily rainfall products in two river basins on the Tibetan Plateau. *Hydrology and Earth System Sciences*, 21, 169–181.
- Liu, Z., Lu, G., He, H., Wu, Z. and He, J. (2017b) Anomalous features of water vapor transport during severe summer and early fall droughts in southwest China. *Water*, 9, 244. <https://doi.org/10.3390/w9040244>.
- Lu, E., Cai, W.Y., Jiang, Z.H., Zhang, Q., Zhang, C.J., Higgins, R.W. and Halpert, M.S. (2014) The day-to-day monitoring of the 2011 severe drought in China. *Climate Dynamics*, 43, 1–9.
- McCabe, G.J. and Wolock, D.M. (2013) Temporal and spatial variability of the global water balance. *Climatic Change*, 120, 375–387.
- McEvoy, D.J., Huntington, J.H.L., Mejia, J.F. and Hobbins, M.T. (2015) Improved seasonal drought forecasts using reference evapotranspiration anomalies. *Geographical Research Letters*, 43(1), 377–385.
- McKee, T.B., Doesken, N.J. and Kleist, J. (1993) The relationship of drought frequency and duration to time steps. In: *8th Conference on Applied Climatology, 17–22 January 1993, Anaheim, CA*. Boston, MA: American Meteorological Society, pp. 179–184.
- Oki, T. and Kanae, S. (2006) Global hydrological cycles and world water resources. *Science*, 313, 1068–1072.
- Palmer, W.C. (1965) *Meteorological drought*. Washington, DC: U.S. Dep. of Commerce, Weather Bureau. Research paper number: 45.
- Peng, J., Niesel, J., Loew, A., Zhang, S. and Wang, J. (2015) Evaluation of satellite and reanalysis soil moisture products over southwest China using ground-based measurements. *Remote Sensing*, 7(11), 15729–15747.
- Peng, J., Loew, A., Merlin, O. and Verhoest, N.E.C. (2017) A review of spatial downscaling of satellite remotely sensed soil moisture. *Reviews of Geophysics*, 55, 341–366. <https://doi.org/10.1002/2016RG000543>.
- Qin, N., Chen, X., Fu, G., Zhai, J. and Xue, X. (2010) Precipitation and temperature trends for the southwest China: 1960–2007. *Hydrological Processes*, 24(25), 3733–3744.
- Schwalm, C.R., Williams, C.A., Schaefer, K., Baldocchi, D., Black, T.A., Goldstein, A.H., Law, B.E., Oechel, W.C., Paw, K.T. and Scott, R.L. (2012) Reduction in carbon uptake during turn of the century drought in western North America. *Nature Geoscience*, 5, 551–556.
- Sheffield, J., Wood, E.F. and Roderick, M.L. (2012) Little change in global drought over the past 60 years. *Nature*, 491, 435–438.
- Shukla, S., Safeeq, M., AghaKouchak, A., Guan, K. and Funk, C. (2015) Temperature impacts on the water year 2014 drought in California. *Geographical Research Letters*, 42, 4384–4393. <https://doi.org/10.1002/2015GL063666>.
- Sun, S.L., Chen, H.S., Ju, W.M., Yu, M., Hua, W.J. and Yin, Y. (2014) On the attribution of the changing hydrological cycle in Poyang Lake Basin, China. *Journal of Hydrology*, 514, 214–225.
- Sun, S.L., Sun, G., Caldwell, P., McNulty, S., Cohen, E., Xiao, J.F. and Zhang, Y. (2015) Drought impacts on ecosystem functions of the U.S. National Forests and Grasslands: Part II assessment results and management implications. *Forest and Ecology Management*, 353, 269–279.
- Sun, S.L., Chen, H.S., Wang, G.J., Li, J.J., Mu, M.Y., Yan, G.X., Xu, B., Huang, J., Wang, J., Zhang, F.M. and Zhu, S.G. (2016) Shift in potential evapotranspiration and its implications for dryness/wetness over southwest China. *Journal of Geophysical Research*, 121, 9342–9355. <https://doi.org/10.1002/2016JD025276>.
- Sun, S.L., Chen, H.S., Sun, G., Ju, W.M., Wang, G.J., Li, X., Yan, G.X., Gao, C.J., Huang, J., Zhang, F.M., Zhu, S.G. and Hua, W.J. (2017a) Attributing the changes in reference evapotranspiration in southwest China using a new separation method. *Journal of Hydrometeorology*, 18(3), 777–798. <https://doi.org/10.1175/JHM-D-16-0118.1>.
- Sun, S.L., Chen, H.S., Ju, W.M., Wang, G.J., Sun, G., Huang, J., Ma, H.D., Gao, C.J., Hua, W.J. and Yan, G.X. (2017b) On the coupling between precipitation and potential evapotranspiration: Contributions to decadal drought anomalies in the southwest China. *Climate Dynamics*, 47, 3779–3797.
- Thornthwaite, C.W. (1948) An approach toward a rational classification of climate. *Geographical Review*, 38(1), 55–94. <https://doi.org/10.2307/210739>.
- Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R. and Sheffield, J. (2013) Global warming and changes in drought. *Nature Climate Change*, 4, 17–22.
- Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J. (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate*, 23, 1696–1718.
- Vicente-Serrano, S.M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J.J., López-Moreno, J.I., Azorin-Molina, C., Revuelto, J., Moran-Tejeda, E. and Sanchez-Lorenzo, A. (2012) Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions*, 16(10), 1–27.
- Vicente-Serrano, S.M., van der Schrier, G., Beguería, S., Azorin-Molina, C. and Lopez-Moreno, J.-I. (2015) Contribution of precipitation and reference evapotranspiration to drought indices under different climates. *Journal of Hydrology*, 526, 42–54.
- Wang, L. and Chen, W. (2012) Characteristics of multi-timescale variabilities of the drought over last 100 years in southwest China. *Advances in Meteorological Science and Technology*, 2(4), 21–26 (in Chinese with English Abstract).
- Wang, L., Chen, W., Zhou, W. and Huang, G. (2015) Drought in southwest China: a review. *Atmospheric and Oceanic Science Letters*, 8(6), 339–344.
- Wei, J., Dirmeyer, P.A. and Guo, Z. (2008) Sensitivities of soil wetness simulation to uncertainties in precipitation and radiation. *Geophysical Research Letters*, 35, L15703. <https://doi.org/10.1029/2008GL034494>.
- Wen, Y. and Liu, S. (1995) Quantitative analysis of the characteristics of rainfall interception of main forest ecosystems in China. *Scientia Silvae Sinicae*, 31, 289–298 (in Chinese with English Abstract).
- Wild, M., Grieser, J. and Schaer, C. (2008) Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological cycle. *Geophysical Research Letters*, 35, L17706. <https://doi.org/10.1029/2008GL034842>.
- Wilhite, D. (2000) Drought as a natural hazard: concepts and definitions. In: Wilhite, D.A. (Ed.) *Drought: A Global Assessment*. London: Routledge, pp. 3–18.
- Williams, A.P., Seager, R., Abatzoglou, J.T., Cook, B.I., Smerdon, J.E. and Cook, E.R. (2015) Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters*, 42(16), 6819–6828.
- Xu, K., Yang, D., Yang, H., Li, Z., Qin, Y. and Shen, Y. (2015) Spatio-temporal variation of drought in China during 1961–2012: a climatic perspective. *Journal of Hydrology*, 526, 253–264.
- Yang, J., Gong, D., Wang, W., Hu, M. and Mao, R. (2012a) Extreme drought event of 2009/2010 over southwestern China. *Meteorology and Atmospheric Physics*, 115, 173–184.

- Yang, X., Li, Z., Feng, Q., He, Y., An, W., Zhang, W., Cao, W., Yu, F., Wang, Y. and Theakstone, W.H. (2012b) The decreasing wind speed in southwestern China during 1969–2009, and possible causes. *Quaternary International*, 263, 71–84.
- Yin, J., Zhan, X., Zheng, Y., Liu, J., Fang, L. and Hain, C.R. (2015a) Enhancing model skill by assimilating SMOPS blended soil moisture product into Noah Land Surface Model. *Journal of Hydrometeorology*, 16(2), 917–931.
- Yin, J., Zheng, Y., Zhan, X., Hain, C.R., Zhai, Q., Duan, C., Wu, R., Liu, J. and Fang, L. (2015b) An assessment of impacts of land-cover changes on root-zone soil moisture. *International Journal of Remote Sensing*, 36(24), 6116–6134.
- Yu, M., Li, Q., Hayes, M.J., Svoboda, M.D. and Heim, R.R. (2014) Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? *International Journal of Climatology*, 34, 545–558.
- Zeng, W., Yu, Z., Wu, S. and Qin, J. (2016) Changes in annual, seasonal and monthly precipitation events and their link with elevation in Sichuan province, China. *International Journal of Climatology*, 36, 2303–2322.
- Zhang, D., Liu, X. and Hong, H. (2013) Assessing the effect of climate change on reference evapotranspiration in China. *Stochastic Environmental Research and Risk Assessment*, 27(8), 1871–1881.
- Zhang, W., Jin, F.F. and Turner, A. (2014) Increasing autumn drought over southern China associated with ENSO regime shift. *Geophysical Research Letters*, 41, 4020–4026.
- Zhang, D., Zhang, Q., Werner, A.D. and Liu, X. (2016a) GRACE-based hydrological drought evaluation of the Yangtze River basin, China. *Journal of Hydrometeorology*, 17(3), 811–828.
- Zhang, J., Sun, F., Xu, J., Chen, Y., Sang, Y.-F. and Liu, C. (2016b) Dependence of trends in and sensitivity of drought over China (1961–2013) on potential evaporation model. *Geophysical Research Letters*, 43, 206–213.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Sun S, Chen H, Li J, et al. Dependence of 3-month Standardized Precipitation-Evapotranspiration Index dryness/wetness sensitivity on climatological precipitation over southwest China. *Int J Climatol*. 2018;38:4568–4578. <https://doi.org/10.1002/joc.5690>