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

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 (ET0) 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 ET0 (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 ET0 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 ET0 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 ET0 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 ET0 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 ET0 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 ET0 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 ET0 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 ET0) 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 the perspective of 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 ET0-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 exerted 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 contributions of precipitation and ET0 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 ET0, respectively. In short, these studies provided critical references for knowing SWC dry/wet conditions and even drought variations in response to climate change from different perspectives. Nevertheless, the dryness/wetness sensitivity to precipitation and ET0 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 ET0 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 ET0 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 (ET0) of 1098.42 mm (989.65 mm). Besides, precipitation (Figure 2; ET0) 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 ET0 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

\[
ET_0 = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \frac{900}{Tave + 273} \cdot Wnd \cdot Vpd}{\Delta + \gamma \cdot (1 + 0.34 \cdot Wnd)},
\]

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; \( \gamma \) (kPa°C) and \( \Delta \) (kPa°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 \( Tave \) (°C) represents mean temperature. For more description about these variables, please see Allen et al. (1998). Notably, the computation of ET0 is conducted on monthly scale, and then annual value can be obtained as the sum of monthly ET0 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 ET0. Subsequently, it
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 ET0 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 ET0 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 ET0 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:

- **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 the factor alone (\( C_i \)) to annual SPEI-3 anomalies can be expressed as

\[
\sum_{k \neq i}^{n} C_{k,j} = V_{\text{SPEI}_i,j}
\]

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

\[
C_{i,j} = \frac{\sum_{k \neq i}^{n} V_{\text{SPEI},k,j} - (n-2) \cdot V_{\text{SPEI},i,j}}{n-1}
\]

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 \( Wnd \).

### 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 \(-188.5 \text{ mm} \) 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>
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<tr>
<th>Experiments</th>
<th>Description</th>
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<tr>
<td>SPEI_CTL</td>
<td>Monthly precipitation, ( Rn ), ( Tave ), ( Wnd ), and ( Vpd ) during 1960–2012</td>
</tr>
<tr>
<td>SPEI_PRE</td>
<td>Monthly precipitation fixed at 52-year (1961–2012) mean; monthly ( Rn ), ( Tave ), ( Wnd ), and ( Vpd ) during 1960–2012</td>
</tr>
<tr>
<td>SPEI_RN</td>
<td>Monthly ( Rn ) fixed at 52-year monthly mean; monthly ( Rn ), ( Tave ), ( Wnd ), and ( Vpd ) during 1960–2012</td>
</tr>
<tr>
<td>SPEI_TAVE</td>
<td>Monthly ( Tave ) fixed at 52-year monthly mean; monthly ( Rn ), ( Tave ), ( Wnd ), and ( Vpd ) during 1960–2012</td>
</tr>
<tr>
<td>SPEI_WND</td>
<td>Monthly ( Wnd ) fixed at 52-year monthly mean; monthly ( Rn ), ( Tave ), ( Wnd ), and ( Vpd ) during 1960–2012</td>
</tr>
<tr>
<td>SPEI_VPD</td>
<td>Monthly ( Vpd ) fixed at 52-year monthly mean; monthly ( Rn ), ( Tave ), ( Wnd ), and ( Vpd ) during 1960–2012</td>
</tr>
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</table>
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 (Spre, ET0, Set0) 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, Spre and Set0 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 Set0 (0.0042 mm) is nearly double of that of Spre (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. Spre and Set0 at each site...
are shown in Figure 4c,d, respectively. Generally, $S_{\text{pre}}$ 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, $S_{\text{pre}}$ is between 0.0015 and 0.0030 mm. For the magnitude of $S_{\text{et0}}$, it shows a clear spatial distribution characterized by an increase from the southeast to the northwest. We also compare the magnitude of $S_{\text{pre}}$ against that of $S_{\text{et0}}$ for each site, and find that $S_{\text{et0}}$ 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 $S_{\text{pre}}$ and $S_{\text{et0}}$ (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 $S_{\text{pre}}$ or $S_{\text{et0}}$ with climatological precipitation ($P_{\text{cli}}$), ET0 ($\text{ET}_{0\text{cli}}$), and aridity ($A_{\text{cli}}$). The results are shown in Figure 5. Both $S_{\text{pre}}$ and $S_{\text{et0}}$ are strongly correlated with $P_{\text{cli}}$ (Figure 5a for $S_{\text{pre}}$ and Figure 5b for $S_{\text{et0}}$) and $A_{\text{cli}}$ (Figure 5e for $S_{\text{pre}}$ and Figure 5f for $S_{\text{et0}}$). In general, the magnitudes of $S_{\text{pre}}$ and $S_{\text{et0}}$ decrease dramatically with increasing $P_{\text{cli}}$ ($A_{\text{cli}}$), especially for areas with higher $P_{\text{cli}}$ (or $A_{\text{cli}}$), indicating that where there is higher $P_{\text{cli}}$ (or $A_{\text{cli}}$), the sensitivity magnitude is lower. To quantify the changes of $S_{\text{pre}}$ ($S_{\text{et0}}$) 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 $S_{\text{pre}}$ ($S_{\text{et0}}$) and $P_{\text{cli}}, \text{ET}_{0\text{cli}},$ and $A_{\text{cli}}$, respectively. However, the relationship between $S_{\text{pre}}$ (Figure 5c; $S_{\text{et0}}$ in Figure 5d) and $\text{ET}_{0\text{cli}}$ is very weak despite of the significant ($p < .01$) correlation. Therefore, $\text{ET}_{0\text{cli}}$ has very limited impacts on $S_{\text{pre}}$ and $S_{\text{et0}}$, and the spatial differences in $S_{\text{pre}}$ ($S_{\text{et0}}$) are potentially controlled by $P_{\text{cli}}$ or $A_{\text{cli}}$. The higher $R$ and the lower root-mean-square error (RMSE) suggest that the relationships between $S_{\text{pre}}$ or $S_{\text{et0}}$ and $P_{\text{cli}}$ are a little stronger than that to $A_{\text{cli}}$. This might be mainly
because of the aridity algorithm includes ET₀ (reflected by a lower relationship of ET₀ with $S_{\text{pre}}$ or $S_{\text{et0}}$), consequently reducing the robustness of the regressions. A multi-linear regression with stepwise algorithm [$S_{\text{pre}}$ ($S_{\text{et0}}$) as dependent variable, but the logarithms of $P_{\text{cli}}$ and $A_{\text{cli}}$ as independent variables] is established, and the results show that $A_{\text{cli}}$ is excluded [$p = 0.13$ (0.33) for the $S_{\text{pre}}$ ($S_{\text{et0}}$) regression] because of the high collinearity between $A_{\text{cli}}$ and $P_{\text{cli}}$. Besides, the correlation analyses show that $R$ between $P_{\text{cli}}$ and $A_{\text{cli}}$ is 0.87 ($p < .01$). These indicates that the dependence of $A_{\text{cli}}$ on $S_{\text{pre}}$ ($S_{\text{et0}}$) can be ultimately attributed to $P_{\text{cli}}$, and therefore we conclude that $S_{\text{pre}}$ ($S_{\text{et0}}$) over SWC logarithmically depends on $P_{\text{cli}}$ with a formulation of $S_{\text{pre}} = -0.002 \times \ln(P_{\text{cli}}) + 0.015$ [$S_{\text{et0}} = 0.0038 \times \ln(P_{\text{cli}}) - 0.031$].

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 ET₀ at the whole SWC and site scales. Despite of precipitation with a predominant impact on SPEI-3 anomalies, ET₀ can have comparable or higher contributions in some years (e.g., before 1980s and in 1990s), which indicates that ET₀ played an important role in dryness/wetness processes in SWC. For dryness/wetness sensitivity to precipitation and ET₀, the SPEI-3 is more sensitive to ET₀ 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, ET₀, 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 ET₀ is stronger than to precipitation over SWC, which is seemingly opposite to our common
knowledge. In this study, we define $S_{\text{pre}}$ 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 $S_{\text{pre}}$ 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.

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