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Analysis of Dry/Wet Variations in the Poyang Lake Basin Using Standardized Precipitation Evapotranspiration Index Based on Two Potential Evapotranspiration Algorithms

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Abstract: Global warming has resulted in unevenly distributed changes in precipitation and evapotranspiration, which has some influence on dry/wet conditions, thus exerting a tremendous impact on national life and the social economy, especially agricultural production. In order to characterize the dry/wet variations in the Poyang Lake basin during 1958–2013, based on the potential evapotranspiration (PET) estimated by the Thornthwaite (TH) and Penman–Monteith (PM) formulas, two types of Standardized Precipitation Evapotranspiration Index (SPEI), namely SPEI_th and SPEI_pm, were calculated in this study. The characteristic of dry/wet variations in the Poyang Lake basin was analyzed and a comparative analysis of two SPEIs was conducted. The results indicate that both SPEI series showed a wet trend in the Poyang Lake basin on an annual scale as well as seasonal scales during 1958–2013, except for spring and autumn. A drying trend was observed in spring, while in autumn, the dry and wet conditions in two SPEIs had opposite trends. However, all trends from two SPEIs were not significant, except for summer SPEI_pm. Meanwhile, significant positive correlations were detected between precipitation and two SPEIs, with the correlation coefficients above 0.95, whereas negative correlations were detected between PET and two SPEIs, with the correlation coefficients ranging from −0.17 to −0.85. This indicates that precipitation was the main climatic factor to determine change in dry/wet conditions in the Poyang Lake basin. Although there were obvious differences between the accumulated values of the Penman–Monteith-based PET (ET_pm) and Thornthwaite-based PET (ET_th), trends in the SPEI_pm series were generally consistent with those in the SPEI_th series, revealing that the method for PET calculation was not critical to the change in dry/wet conditions. Moreover, the results of the conditional probability of SPEI_pm and SPEI_th show that both SPEI_pm and SPEI_th could detect wet or dry events that were identified by SPEI_pm or SPEI_th.

Keywords: dry/wet conditions; potential evapotranspiration (PET); Standardized Precipitation Evapotranspiration Index (SPEI); Poyang Lake basin

1. Introduction

According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), global warming is prevailing throughout the world, with the global temperature rising by 0.91 °C over the past 100 years, and the global warming trend will continue [1]. Various studies have indicated that climate warming is expected to intensify atmospheric circulation and hydrological circle, then alter precipitation patterns and evapotranspiration [2,3]. Furthermore, changes in precipitation and evapotranspiration will affect the balance of the surface water budget. This can induce more frequent meteorological events, such as floods and droughts, and ultimately change local dry and wet conditions and their spatial and temporal distribution, thus exerting a severe impact on natural ecosystems, human health, social economy, and especially agricultural production [4–6]. Hence, it is of great importance to further study the characteristics of dry and wet variations for efficient water resource management and adaptation strategies development of climate change.

In recent decades, some scholars have explored the mechanisms of dry and wet changes from the perspective of precipitation anomalies, since precipitation is a key factor determining local dry and wet conditions [7,8]. Also, various indices have been developed and widely used for monitoring local dry and wet conditions. Among these, the standardized precipitation index (SPI) proposed by McKee et al. [9] has already been widely used to characterize dry and wet conditions in many countries and regions due to its simplicity and variable timescales, which requires only the precipitation as input data to quantify water deficit and surplus with respect to long-term normal conditions for multiple time scales [3,6,10–12]. However, one of the main disadvantages of the SPI is that it only uses precipitation data, and the effect of evapotranspiration is not considered [5,13–15]. In fact, with global warming, variations in evapotranspiration caused by remarkable changes in surface meteorological factors, such as temperature, have had an important impact on dry and wet conditions over the past several decades [16,17]. The indicators constructed by the single variable of precipitation cannot reflect the influence of warming or cooling on dry and wet conditions, although precipitation is still an important factor determining the dry and wet changes of the surface [18].

Furthermore, dry–wet variations in certain regions under natural conditions result from the water influx (mainly derived from precipitation) and outflux (evapotranspiration) of the land, which is essentially the interaction of precipitation and evapotranspiration [19]. Therefore, in the context of climate change, indices of dry–wet changes only considering precipitation are confined to illustrating the extent and intensity of dry and wet conditions. In order to comprehensively consider the effects of precipitation, evapotranspiration, and to assess the dry–wet variations reasonably on multi-time scales, a standard precipitation evapotranspiration index (SPEI) was recently proposed by Vicente-Serrano et al. [15,20]. Frequently used by researchers in dissecting the spatiotemporal characteristics and changing tendency in different regions, SPEI has been proven to be more effective to represent wetness and dryness under the background of global climate change [13,14,21–26].

Since it is difficult to obtain the long-term actual evapotranspiration data, potential evapotranspiration (PET), as a substitute for the actual evapotranspiration, is commonly used with precipitation to calculate the balance between water supply and demand in the calculation of SPEI [19,27]. Traditionally, in the original SPEI, PET was estimated based on the Thornthwaite (TH) formula, with only one parameter of temperature [28]. Although the TH formula was simple to apply due to its low data requirements, it can generate a bias in estimations as a simplified PET approach, which would have some influence on the SPEI [18]. For instance, it underestimated evapotranspiration in arid and semi-arid regions, yet overestimated evapotranspiration in humid and tropical regions [29–31]. In recent years, numerous studies worldwide have shown that the Penman–Monteith (PM) equation is the most reasonable approach and performs best in comparison with other PET methods under various climatic conditions, since this method combined mass transfer and energy balance with temperature and vegetation conductance [32–36].

The Poyang Lake basin is one of the major agricultural-orientated areas in China and plays an indispensable role in national food security [37]. Meanwhile, the Poyang Lake is also crucial for water security and ecosystem security for the lower reaches of the Yangtze River [38]. However, influenced by the East Asian monsoon, the seasonal and annual variations in precipitation in the Poyang Lake basin are relatively severe, leading to frequent floods and droughts, which cause huge damage to the environment and the agricultural economy [37–40]. Especially after 1990, the occurrence frequency and intensity of floods and droughts have increased significantly in the Poyang Lake basin because of the changes in precipitation patterns and temperature increasement caused by climate warming [41–44]. Thus, many investigations have been conducted on variations in local dry/wet conditions in the Poyang

Lake basin. Nevertheless, previous studies usually focused on the spatiotemporal distribution of dry/wet conditions by the SPI and China-Z index methods [37,39,45]. Few of them have investigated the variations and trends of dry/wet conditions in Poyang Lake basin using SPEI to integrate the input (precipitation) and output (evapotranspiration). In particular, the impacts of various SPEIs calculated with the different PET algorithms on characteristics of the dry/wet variations in Poyang Lake basin have not been implemented so far.

Therefore, the aim of this study is to describe the variations in dry/wet conditions in Poyang Lake basin and investigate the impacts of various SPEIs on the characteristics of dry/wet conditions. In this paper, the SPEI was applied to characterize the dry/wet conditions in the Poyang Lake basin during 1958–2013. As two representative parameterizations for PET calculation, the Penman–Monteith and the Thornthwaite equations were employed to obtain two types of SPEI, namely the Penman–Monteith equation based SPEI (SPEI_pm) and the Thornthwaite equation based SPEI (SPEI_th). The spatiotemporal characteristics of dry/wet conditions in Poyang Lake basin were analyzed, and further comparison was conducted with two types of SPEI. This paper is organized as follows: a brief introduction of the study area and data is given in Section 2; methods of analysis are described in Section 2; the results and discussion are presented in Section 3. Finally, conclusions are given in Section 4.

2. Data and Methods

2.1. Study Area and Meteorological Data

The Poyang Lake basin is located in the middle and lower reaches of the Yangtze River, China, between 115°47′–116°45′ E longitude and 28°22′–29°45′ N latitude. It consists of five river watersheds and lake regions (Poyang Lake and its vicinity areas). These five rivers (Ganjiang River, Fuhe River, Xinjiang River, Raohe River, and Xiushui River) all flow into Poyang Lake, which is the largest freshwater lake in China, and eventually discharge into the Yangtze River (Figure 1). The Poyang Lake basin covers an area of 16.22×10^4 km^2, which accounts for 9% of the drainage area of the Yangtze River basin and nearly 97% of Jiangxi Province. The landscape varies from high mountainous and hilly areas in the West, South, and East to alluvial plains in the lower reaches of the primary watercourses. The basin presents a subtropical humid monsoon climate with a mean annual precipitation of 1622.1 mm and mean annual temperature of 17.8 °C. The distribution of annual precipitation is uneven, with approximately 50% occurring in March to June. Temperature is subject to a high seasonal variability and increases rapidly from January, peaks in July, and then decreases [40].

In this study, 13 national meteorological stations in the Poyang Lake basin were selected (Table 1). The distribution of meteorological stations in the basin is shown in Figure 1. Daily meteorological data from 1951 to 2013 were obtained from the National Meteorological Information Center of China (CMA) (http://data.cma.cn), including precipitation, mean temperature, the minimum and maximum air temperature, relative humidity, wind speed (at 10 m height), and sunshine duration. These data have been widely used for different previous studies and the data quality has been proven to be reliable [41–45]. According to the completeness and quality of data records, the total 13 stations with better quality control for the period 1958–2013 were selected to use for analysis of dry/wet conditions in the Poyang Lake basin. Fewer missing data in specific stations were substituted with the average values of the same period (the missing day) in all other years without missing data.

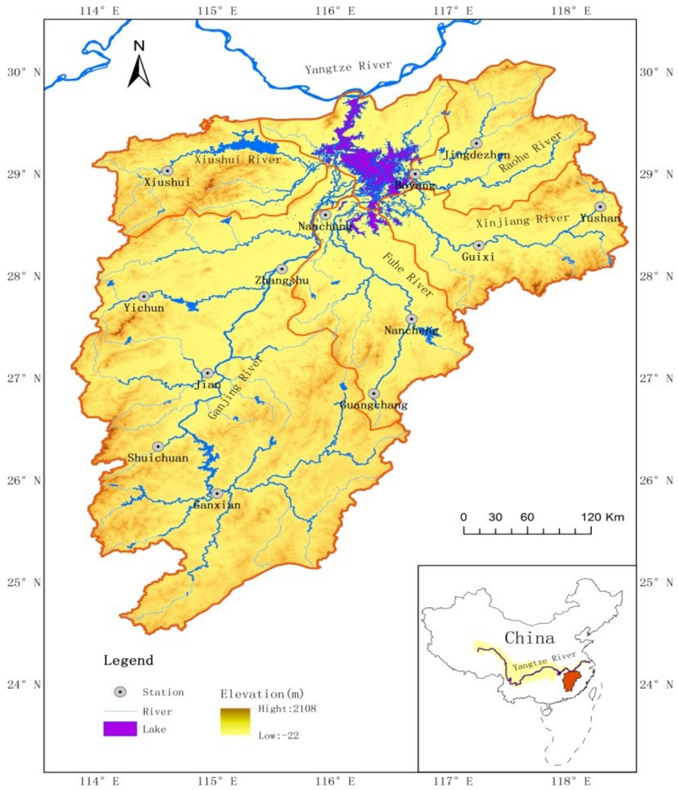


Figure 1. Location of the Poyang Lake basin and the distribution of meteorological stations.

Table 1. Basic information about 13 meteorological stations in Poyang Lake Basin.

ID	Station Name	Longitude (°E)	Latitude (°N)	Altitude (m)	Time Period
57598	Xiushui	114.58	29.03	146.8	1953–2013
57793	Yichun	114.38	27.80	131.3	1953–2013
57799	Jian	114.92	27.05	71.2	1952–2013
57896	Shuichuan	114.50	26.33	126.1	1951–2013
57993	Ganxian	115.00	25.87	137.5	1951–2013
58519	Boyang	116.68	29.00	40.1	1955–2013
58527	Jingdezhen	117.20	29.30	61.5	1953–2013
58606	Nanchang	115.92	28.60	46.9	1951–2013
58608	Zhangshu	115.55	28.07	30.4	1957–2013
58626	Guixi	117.22	28.30	51.2	1953–2013
58634	Yushan	118.25	28.68	116.3	1951–2013
58715	Nancheng	116.65	27.58	80.8	1953–2013
58813	Guangchang	116.33	26.85	143.8	1954–2013

2.2. Methods

2.2.1. PET Estimation Methods

Several different methods have been developed to estimate the PET from measured meteorological data. These methods can be roughly grouped into three categories, that is, solar radiation-based methods, temperature-based methods, and combination approach-based methods [29]. Among these, the commonly used methods were the PM method and TH method [33]. The PM method was recognized as the most reasonable approach and performed best in comparison with other PET methods under various climatic conditions [32–36]. However, the PM method required more meteorological parameters, such as solar radiation, wind speed, temperature, and relative humidity, which were often difficult to obtain for the majority of regions due to the limited meteorological stations. The TH method only required the monthly average temperature and the latitude of the stations, which were easy to obtain, and it was simple to apply [25]. In this study, the TH method and PM method were employed to compute PET.

- Thornthwaite (TH) method

The TH method is one of the most commonly used approaches for estimating PET [28,31]. Following this method, the monthly PET for the month i was calculated according to:

$$PET_i = 16 \times (\frac{N_i}{12}) \times (\frac{M_i}{30}) \times (10 \times \frac{T_i}{I})^{\alpha}, \tag{1}$$

where PET_i, N_i, and M_i are the monthly potential evapotranspiration, the monthly mean sunshine hours, and the number of days for the month i, respectively; T_i is the monthly mean temperature (when T_m is a negative value, ET_m takes zero); I is the heat index; α is a coefficient based on I.

For I and α, the respective calculation formula can be expressed as:

$$\alpha = 0.49239 + 1.792 \times 10^{-2} I - 7.71 \times 10^{-5} I^2 + 6.75 \times 10^{-7} I^3; \tag{2}$$

$$I = \sum_{m=1}^{12} (\frac{T_m}{5})^{1.514}. \tag{3}$$

The detailed calculation can be found in studies related to [28,31].

- Penman–Monteith (PM) method

Based on theories of energy balance and aerodynamics, the PM method is considered to be more accurate and suitable for estimating PET than many other methods [31–36]. It has been recommended by several international organizations, such as the Food and Agriculture Organization (FAO) and the International Commission on Irrigation and Drainage (ICID), for calculating PET [20,22]. The PM method for calculating daily PET can be expressed as:

$$PET_d = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \tag{4}$$

where PET_d is the daily potential evapotranspiration (mm·d^{-1}), Δ represents the slope of the saturation vapor pressure–temperature curve (kPa·°C^{-1}), R_n is the net radiation at the surface (MJ/(m^2·d)), G is the soil heat flux, (MJ/(m^2·d)), γ is the psychometric constant (kPa·°C^{-1}), u_2 is the mean daily wind speed at 2 m height (m·s^{-1}), T is the mean daily air temperature (°C), e_s is the saturation vapor pressure (kPa), and e_a is the actual atmospheric water vapor pressure (kPa).

More detailed information on the PM method can be found in reference [33].

2.2.2. SPI Calculation

The SPI was proposed to assess and quantify drought events on multiple time scales based on the long-term precipitation data [9]. Due to its simplicity and relatively lower data demand, the SPI has been widely applied for drought analysis [3,5,6,9]. To calculate the SPI at a given time scale (i.e., 3, 6, 12, and 24 months), the first step was to fit a probability density function to a given monthly precipitation series. For SPI calculation, the most commonly used distribution was the two-parameter gamma distribution with a shape parameter (α) and a scale parameter (β). The maximum likelihood solutions were used to optimally estimate the parameters, α and β. Next, the optimized parameters can be used to find the cumulative probability ($G(x)$) of the observed precipitation for the given time scale. Since the gamma function was undefined for x = 0, when a precipitation may contain zeros, the cumulative probability ($H(x)$) became:

$$H(x) = q + (1 - q)G(x), \tag{5}$$

where q is the probability of a zero on specified time scale. The cumulative probability, $H(x)$, can be then transformed to a standard normal distribution to obtain the SPI. Further details on the calculation of the SPI have been extensively described in publications, such as Mckee et al. [9].

2.2.3. SPEI Calculation

SPEI is a drought index based on precipitation and PET, which combines the multi-scale convenience of time and temperature effects for drought assessment, and it is considered to be more suitable for drought monitoring and analysis under climate change [20–26]. In this study, SPEI was applied to describe the variations in the dry and wet conditions of the Poyang Lake basin, and further comparison was conducted with two types of SPEI based on two sets of PET data calculated by TH and PM formulas. The calculation of SPEI is briefly described as follows:

A climatic water balance (D) was determined by the difference between precipitation (P) and PET for the month i according to:

$$D_i = P_i - PET_i, \tag{6}$$

where monthly PET is calculated by the TH and the PM methods.

The calculated D values were aggregated at different time scales (i.e., 3, 6, 12 months), following the same procedure as that for the SPI. And then, the three-parameter log-logistic distribution was applied to calculate the SPEI based on the standardized D series. For the D series of all time scales, the accumulative function $F(x)$ was given by:

$$F(x) = \left[1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right]^{-1}, \tag{7}$$

where α, β, and γ are the scale, shape, and origin parameters, respectively [20].

Thus, SPEI can be then easily calculated as the standardized values of $F(x)$, with the following formula:

$$SPEI = W - \frac{2.515517 + 0.802853W + 0.010328W^2}{1 + 1.432788W + 0.189269W^2 + 0.001308W^3}, \tag{8}$$

where,

$$W = \sqrt{-2\ln(p)} \quad for \quad p \le 0.5 \quad , \tag{9}$$

and $p = 1 - F(x)$, which is the probability of exceeding a determined D value. If $p > 0.5$, p will be replaced by $1 - p$ and the sign of the resultant SPEI will be reversed.

According to the SPEI/SPI values, dry and wet conditions can be classified as in Table 2. If the SPEI/SPI value is above 1.0, this indicates a wet state, and the larger the positive value of SPEI/SPI, the wetter it is. If the SPEI/SPI value is less than or equal to −1.0, this indicates a dry state. The more negative the SPEI value, the more severe the drought. If SPEI/SPI value is between −1.0 and 1.0, this indicates a normal state. To explore the variations in dry and wet conditions at seasonal and annual time scales, the SPEI values for 3- and 12-month scales were calculated in this study to analyze the characteristics of dry/wet conditions in the Poyang Lake basin.

Table 2. Categorization of dryness/wetness grade by the SPEI/SPI.

Categories	SPEI/SPI Values
Extremely wet	More than 2.00
Severely wet	1.5 to 1.99
Moderately wet	1.00 to 1.49
Near normal	−0.99 to 0.99
Moderate drought	−1.49 to −1.00
Severe drought	−1.99 to −1.50
Extreme drought	Less than −2.00

2.2.4. Trend Analysis

Since the non-parametric Mann–Kendall (MK) test has the ability to quantify the trend and significance of the long time-series data, it has been widely applied for trend analysis in hydrological and climatological data time series [22,46,47]. In this study, the MK test was used to detect the changing trends of dry and wet conditions in the Poyang Lake basin. The standardized test statistic (Z) was defined as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \ \ S > 0 \\ 0 & if \ \ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \ \ S < 0 \end{cases}, \tag{10}$$

where S is the test statistic given as Formula (11), Var is the variance of S calculated as Formula (12):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i); \tag{11}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(t_i - 1)(2t_i + 5)}{18}, \tag{12}$$

where n is the length of the data series, t is the extent of any given tie.

Based on the MK test, a positive value of Z denotes an upward trend in the corresponding time series, while a negative Z value shows a downward trend. The testing of trends is performed at the specific α significance level. Given a certain significance level α, if $|Z| \geq Z_{1-\alpha/2}$, it means the trend is statistically significant at the significance level α. Generally speaking, when the significance level α is equal to 0.05 and 0.1, $|Z|$ is equal to 1.96 and 1.64, respectively. In this study, the significance levels of 0.05 and 0.1 were used to discuss the MK trends of dry and wet conditions in the Poyang Lake basin.

The magnitude of the trend can be estimated using Sen's slope β, developed by Sen in 1968 [48], which was defined as:

$$\beta = Median\left(\frac{x_j - x_i}{j - i}\right) \quad \forall i < j \ , \tag{13}$$

where x_i and x_j are the ith and jth values of the data series. A positive (negative) value of β denotes an upward (downward) trend.

In addition, to investigate the spatial variability of the two SPEIs on seasonal and annual timescales over Poyang Lake basin, the co-kriging method was used with the altitude (extracted from a digital elevation model (DEM) with an accuracy of 30 m) as an independent variable and the SPEI as dependent one [49–51]. In this study, the co-kriging method was performed using ArcGis 10.2 software. Meanwhile, considering the variation in topography and the uneven distribution of meteorological stations across the Poyang Lake basin, the Thiessen polygon method was used to calculate an areal mean value for precipitation and other climatic variables. The method was an area-based weighting method commonly used for calculating the areal mean value of precipitation in the water resources and hydrology field [45,52]. It determined the weight by calculating the percentage of area represented by each meteorological station [45].

3. Results and Discussion

3.1. Spatial and Temporal Variation in the SPEI_pm and SPEI_th

Based on the aforementioned methodology, two types of SPEI, namely SPEI_pm and SPEI_th, were calculated on the 3- and 12-month time scales for all stations during 1958–2013 using precipitation and two sets of PET data, in which PET was estimated by the TH and FAO56 PM formulas, respectively. Meanwhile, the monthly SPEI_pm and SPEI_th on the 3- and 12-month time scales were calculated to obtain the overall SPEI values of Poyang Lake basin, using the precipitation and PET averaged over all 13 stations by the Thiessen polygon method. The SPEI values for the 3-month time scale reflected the status of seasonal water deficit, while the SPEI values for the 12-month time scale indicated the status of the year-round water deficit [24]. Here, in this study, the SPEI values of spring, summer, autumn, and winter were denoted by the May, August, November, and February SPEI values for the 3-month time scales, respectively, and the annual SPEI value was denoted by the December SPEI values for the 12-month time scales.

3.1.1. Temporal Variation

Figure 2 shows the annual and seasonal variations in the SPEI_pm and SPEI_th series in the Poyang Lake basin from 1958 to 2013. The annual SPEI_pm and SPEI_th had increasing trends in the Poyang Lake basin during the period 1958–2013 (Figure 2a), with a changing rate of 0.0087/a and 0.0014/a, respectively. The SPEI_th increased slightly in summer and winter (Figure 2c,e), but it decreased slightly in spring and autumn (Figure 2b,d). However, all trends from the SPEI_th series were not significant. The SPEI_pm had increasing trends in summer, autumn, and winter. Especially in summer, the increasing trend was more significant. Meanwhile, it decreased slightly in spring.

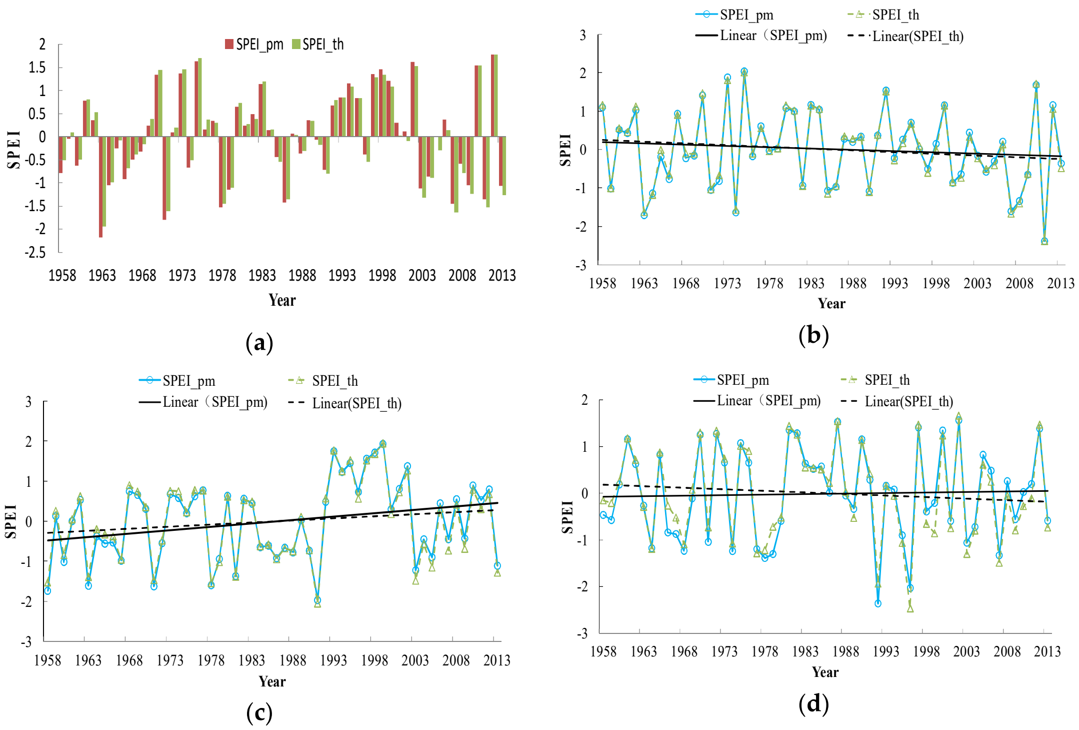
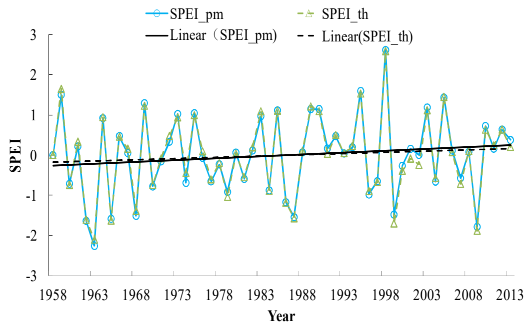


Figure 2. *Cont.*



(**e**)

Figure 2. Variation in averaged annual (**a**), spring (**b**), summer (**c**), autumn (**d**), and winter (**e**) SPEI_pm and SPEI_th in the Poyang Lake basin from 1958 to 2013.

These results show that trends in the SPEI_pm series were generally consistent with those in the SPEI_th series. During 1958–2013, wetting tendencies were observed in the watershed in both the SPEI_pm and SPEI_th series on an annual scale as well as seasonal scales, for which the trend of the former was more obvious than the latter, except for spring and autumn. A drying trend was observed in the SPEI_pm and SPEI_th series in spring, with a changing rate of −0.0067/a and −0.0092/a, respectively. Considering the importance of spring to crop growth, the drying trend in the spring might have an impact on crop yields. In autumn, the dry and wet conditions in two types of SPEI series had opposite trends. There was a wetting trend in the autumn SPEI_pm series and a drying trend in the autumn SPEI_th series. In addition, the SPEI_pm in summer exhibited the greatest trend magnitude of all the seasons. Overall, the SPEI values fluctuated mainly between −2 and 2. According to the dry–wet grade in Table 2, the dry–wet grade in the basin mainly changed between moderate drought and moderate humidity.

3.1.2. Spatial Variation

To further obtain the spatial patterns of the SPEI_pm and SPEI_th series in the Poyang Lake basin, the Z values and Sen's slope β for 13 stations were calculated to analyze the trends for the two types of annual and seasonal SPEI series during 1958–2013, based on the MK test method (Figure 3). The positive and negative trends, which represented trends towards both wetter and drier conditions, were detected. The MK trends of SPEI_pm and SPEI_th on an annual scale and seasonal scales in the whole Poyang Lake basin are listed in Table 3.

Table 3. MK (Mann–Kendall) trends of SPEI_pm and SPEI_th on an annual scale and seasonal scales in the Poyang Lake basin.

Time	SPEI_pm			SPEI_th			SPI		
	Z	**Trend**	***P* Value**	***Z***	**Trend**	***P* Value**	***Z***	**Trend**	***P* Value**
Spring	−0.6997	−0.0067	0.4841	−1.0389	−0.0101	0.2988	−0.7845	−0.0054	0.4327
Summer	2.0708*	0.0160	0.0384	1.0955	0.0094	0.2733	1.6043	0.0124	0.1086
Autumn	0.1343	0.0015	0.8932	−0.8552	−0.0085	0.3925	−0.2474	−0.0027	0.8046
Winter	1.2196	0.0084	0.2226	0.7985	0.0059	0.4246	1.0744	0.0074	0.2826
Year	1.0813	0.0112	0.2795	0.2191	0.0024	0.8266	0.6573	0.0066	0.5110

Notes: * denotes trends statistically significant *at* $P < 0.05$.

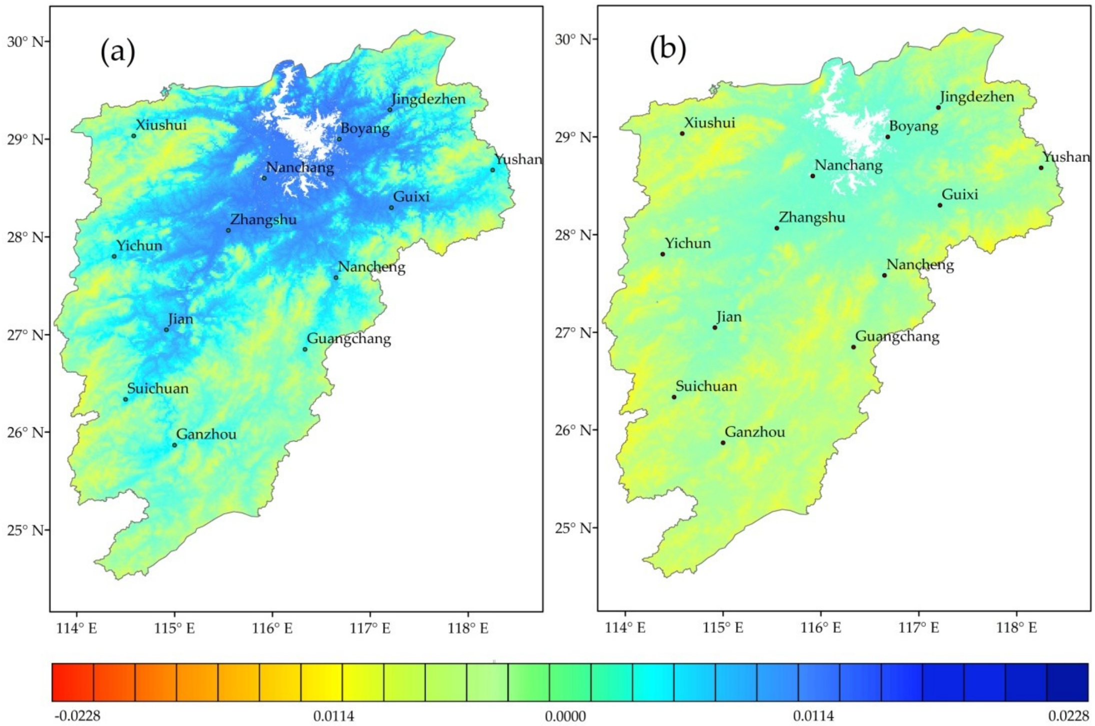


Figure 3. Spatial distribution of trends of annual SPEI_pm (**a**) and SPEI_th (**b**) during 1958–2013.

Figure 3 showed the spatial distribution pattern of the annual SPEI series from 1958 to 2013. It can be concluded that some differences in the trend magnitude of wet and dry variations between the two types of SPEI series existed. The predominant evolution of annual SPEI_pm in the whole Poyang Lake basin strengthened. This occurred despite slightly decreased trends from two stations (Xiushui, Guangchang) during 1958–2013. However, trends in the SPEI_pm series from all stations were not distinct, except for Zhangshu and Guixi ($P < 0.1$). With SPEI_th to detect the annual trends, only about half of all stations in Poyang Lake basin showed an increasing trend. Similarly, trends from the SPEI_th series were not significant. Compared with SPEI_th, SPEI_pm showed a larger range of wetting and a much clearer trend of wetting in northern Poyang Lake basin.

Figure 4 demonstrated the spatial distribution pattern of SPEI values in four seasons. Almost all meteorological stations were characterized by increasing SPEI trends in summer (Figure 4c,d) and winter (Figure 4g,h). Especially for the summer SPEI_pm, stations in northeast Poyang Lake basin such as Jindezheng, Nancheng and Guixi were characterized by trends significant at the 95% confidence level. This indicated that a wet tendency dominated Poyang Lake basin in summer. Meanwhile, a drying trend was observed in almost all the stations in the spring (Figure 4a,b). This indicated that a dry tendency dominated Poyang Lake basin in spring despite of the insignificant trends at the 95% confidence level. Figure 3e showed that, almost two-thirds of the meteorological stations were characterized by increasing trends when using the SPEI_pm to detect the trends in autumn, whereas in terms of SPEI_th, all the stations were characterized by decreasing trends in autumn (Figure 4f). Moreover, all trends from the two SPEI series in autumn were not significant.

On the whole, the above results showed that that there was a wetting tendency in the Poyang Lake basin. However, trends in the SPEI_pm were relatively obvious, compared to the SPEI_th. The magnitude of trend in the SPEI_pm was slightly greater than that in the SPEI_th at the seasonal scales as well as annual scale in Poyang Lake basin during 1958–2013.

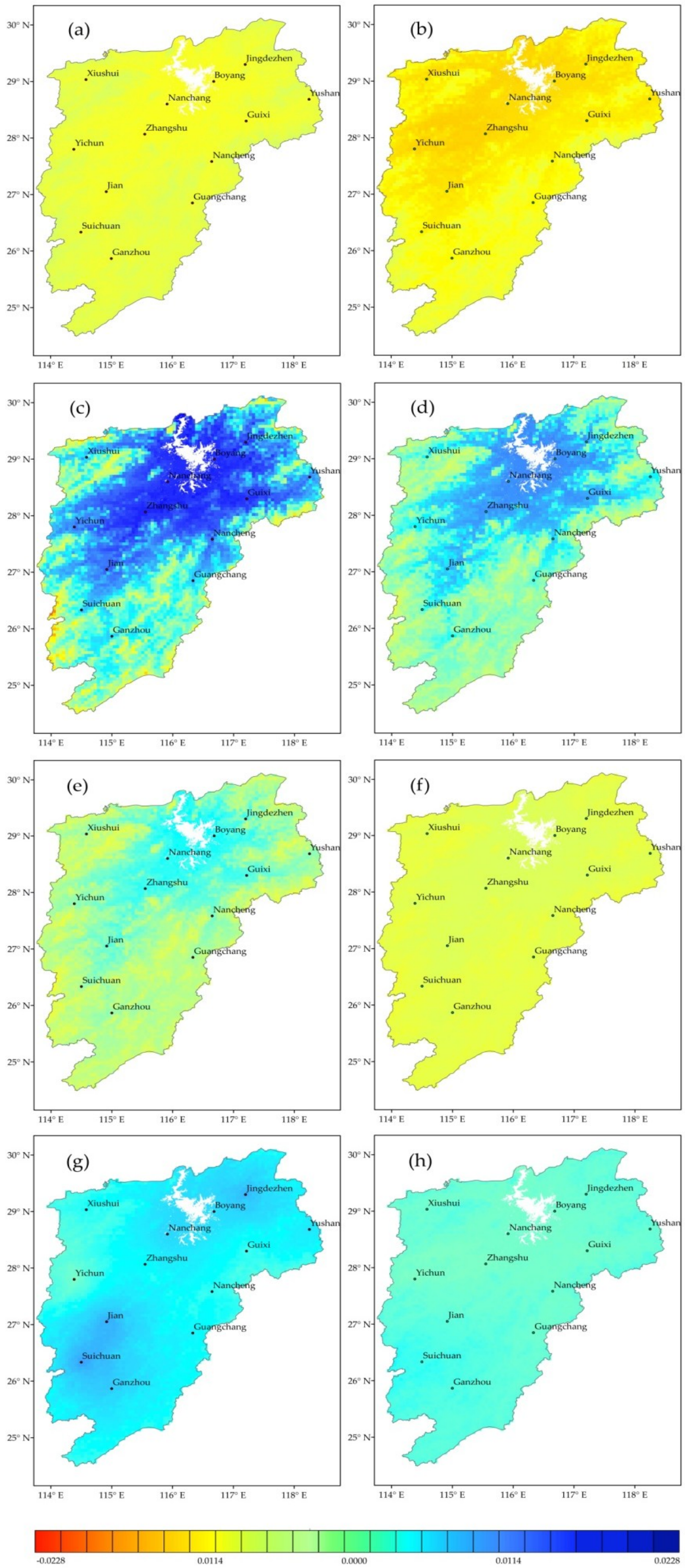


Figure 4. Spatial distribution of the trends of spring (**a**,**b**), summer (**c**,**d**), autumn (**e**,**f**), and winter (**g**,**h**) SPEI_pm (**a**,**c**,**e**,**g**) and SPEI_th (**b**,**d**,**f**,**h**) during 1958–2013.

3.2. Frequency of Dry and Wet Class Based on the SPEI_pm and SPEI_th

Figure 5 showed the frequency of different categories calculated from SPEI_pm and SPEI_th. As shown in Figure 5a, it can be seen that the normal class, either based on SPEI_pm or SPEI_th, had the highest occurrence, accounting for about 66%, and the frequency of extreme dry and wet classes was the lowest, less than 2.0%. The frequency of drought identified by SPEI_pm (SPEI_th) in the Poyang Lake basin was 15.5% (15.8%), of which the occurrence frequency of moderate drought, severe drought, and extreme drought were 8.1% (8.51%), 5.8% (5.37%) and 1.64% (1.94%), respectively. As for the occurrence of wet episode in the Poyang Lake basin, the frequency of wet episode identified by SPEI_pm (SPEI_th) was 18.1% (17.5%), of which the occurrence frequency of moderate wet, severe wet, and extreme wet were 11.9% (10.9%), 4.9% (5.37%) and 1.2% (1.2%), respectively.

Figure 5b–e further showed the frequency of dryness and wetness of different categories at seasonal scales. From a seasonal perspective, the highest frequency of dry episode, either based on SPEI_pm or SPEI_th, occurred in autumn with a frequency of 17.6%, and then followed by about 15% in winter. For wet episode calculated from SPEI_pm and SPEI_th, the most frequent occurrence was in winter, varying from 18% to 20%, and the second-highest frequency occurred in spring with the same frequency of 18.8%. The results here generally concur with Ye et al. [53]. Ye et al. showed that the most frequent occurrence of wet episode was in November, December, and February.

Overall, the above results indicated that the frequencies of dryness and wetness of different categories calculated from SPEI_pm were generally consistent with those from SPEI_th, but compared to the SPEI_th, the occurrence of wet episode was more frequent in the SPEI_pm at seasonal scale as well as annual scale in Poyang Lake basin during 1958 to 2013.

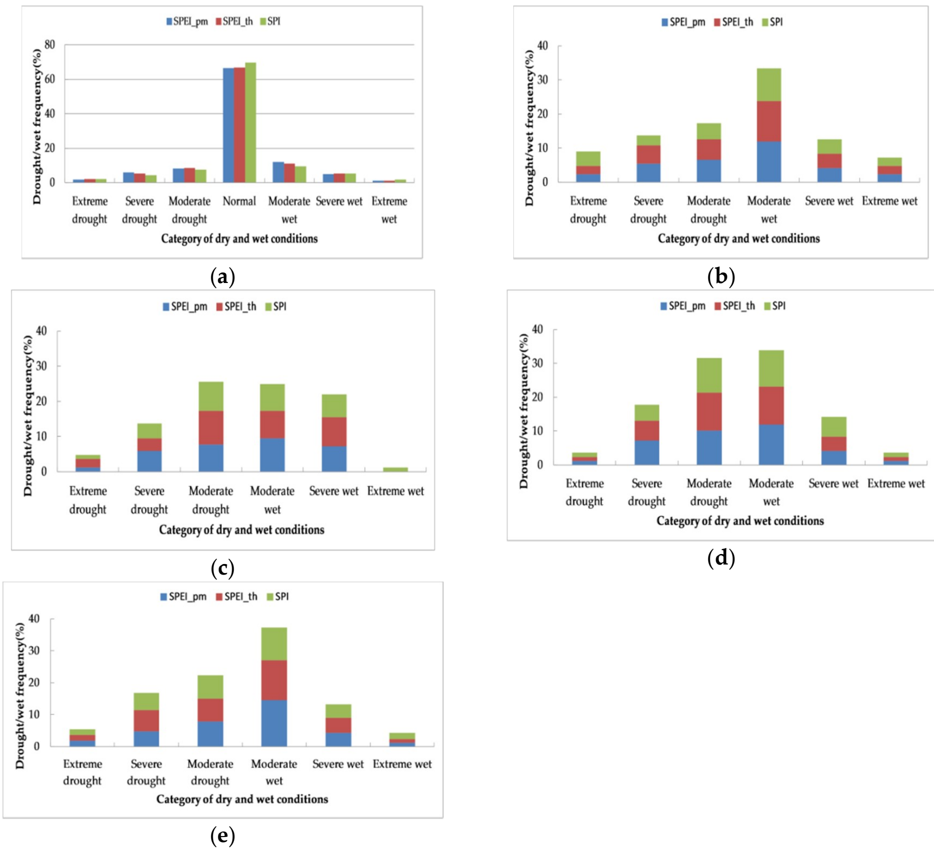


Figure 5. The frequencies of dry and wet conditions of different categories at annual (**a**), spring (**b**), summer (**c**), autumn (**d**), and winter (**e**) scales in the Poyang Lake basin during 1958–2013.

3.3. Analysis of Differences between SPEI_pm and SPEI_th

3.3.1. Variation of Sen's Slope within 30-Year Window

To further explore the intensity and trends of dry/wet variations with time in the Poyang Lake basin, the variation of Sen's slope within a 30-year window for the two types of SPEI series on annual scale and seasonal scales during 1958–2013 were calculated based on the MK test method (Figure 6). As shown in Figure 6, the year of 1958, named as $Year_{1958}$, represented the 30-year period of 1958–1987, the year of 1959, expressed as $Year_{1959}$, represented the 30-year period of 1959–1988, and others were similar.

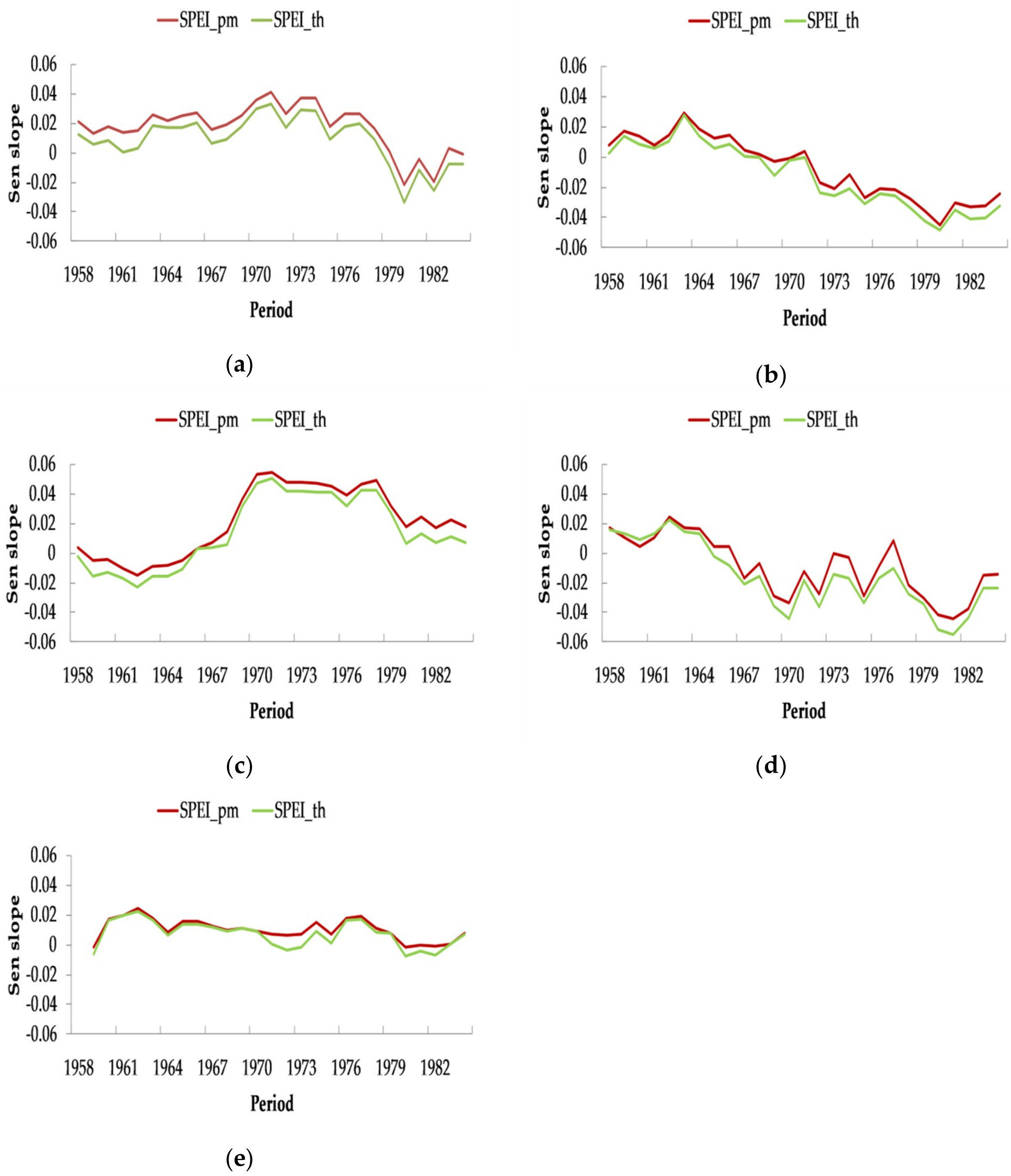


Figure 6. Variation in Sen's slope in annual (**a**), spring (**b**), summer (**c**), autumn (**d**), winter (**e**) SPEI_pm and SPEI_th in the Poyang Lake basin from 1958 to 2013.

From Figure 6, it could be observed that the annual SPEI_pm and SPEI_th had increasing trends in the Poyang Lake basin before $Year_{1979}$, while they had decreasing trends after $Year_{1979}$. Similar to annual SPEI changes, the trends of the two SPEIs increased slightly in spring and autumn, and then decreased. In spring, the two SPEIs had increasing trends before $Year_{1968}$, and then decreased. In autumn, the two SPEIs had increasing trends in the Poyang Lake basin before $Year_{1966}$, while they had decreasing trends after $Year_{1966}$. Contrary to the changes in spring and autumn, in summer, the SPEI_pm and SPEI_th had decreasing trends before $Year_{1966}$, and then increased, whereas in winter, the two SPEIs had increasing trends before $Year_{1980}$, and then decreased, and after $Year_{1983}$ they increased again. Generally, trends in the SPEI_pm series were consistent with those in the SPEI_th series within the 30-year window, but the magnitude of the trends in the former was slightly greater than that in the latter on the seasonal scales as well as the annual scale in the Poyang Lake basin.

Compared with the trends of the two SPEIs during the period 1958–2013 (Table 3), there were some differences in annual SPEI_pm, annual SPEI_th, and autumn SPEI_pm during the period 1984–2013. During the period 1958–2013, the annual SPEI_pm and SPEI_th had increasing trends, while the annual SPEI_pm and SPEI_th had decreasing trends in $Year_{1984}$. In autumn, the SPEI_pm had increasing trends during the period 1958–2013, but the autumn SPEI_pm had decreasing trends in $Year_{1984}$. Considering that the trend of $Year_{1984}$ was only the part of the variation of Sen's slope with time within the 30-year window in the time series with a 55-year series length, therefore, the trends calculated with the 55-year series length (from 1958 to 2013) were more reasonable than the trends calculated with 30-year series length (from 1984 to 2013).

3.3.2. The Relationships between Precipitation, PET and SPEI_th/SPEI_pm

From Figure A1, it can be observed that before 1997, the difference between the two SPEIs on the annual scale as well as seasonal scales was mostly negative, indicating that the dry and wet state identified by SPEI_pm was obviously drier than that identified by SPEI_th, while the difference was mostly positive after 1997, which showed that the dry and wet state detected by SPEI_pm was more wetter than that detected by SPEI_th. The results indicated that there were still some slight differences between SPEI_th and SPEI_pm, although, as a whole, the SPEI based on the two PET estimators was fairly similar in magnitude. Therefore, it was necessary to analyze the variation of precipitation and PET in order to illustrate the causes of the differences.

Figure 7 illustrated the evolution of precipitation and PET in the Poyang Lake basin on an annual scale and seasonal scales. Figure 7 showed that annual precipitation, summer and winter precipitation presented an increasing trend, while precipitation in spring and autumn showed a slightly decreasing trend. However, all trends were not significant. Meanwhile, compared with SPEI_th and SPEI_pm (Figure 2), the trend of the two SPEI series was almost consistent with the precipitation anomaly (figure not shown). The larger the precipitation anomaly, the greater the value of SPEI, and vice versa. But in autumn, the corresponding relationship between precipitation and SPEI_pm was different, that is, precipitation decreased, and SPEI_pm increased. This shows that precipitation could indicate changes in wetness and dryness conditions, but it also had limitations in some seasons, in which wet and dry changes were more affected by PET.

Based on the equations mentioned in Section 2.2, the accumulated values of PM-based PET (ET_pm) and TH-based PET (ET_th) on an annual scale and seasonal scales in the Poyang Lake basin from 1958 to 2013 were calculated (Figure 7). In general, ET_pm was higher than ET_th, but the difference between ET_pm and ET_th was decreasing in recent decades, except for summer, in which ET_th was higher than ET_pm, and the difference between them was increasing. After 1997, the difference between ET_pm and ET_th changed steadily. In addition, ET_pm and ET_th had opposite trends on an annual scale and seasonal scales, ET_pm had decreasing trends, while ET_th had increasing trends from 1958 to 2013, except for spring. In spring, both ET_pm and ET_th had an increasing trend.

Comparing the calculated results of PET using two estimators, it can be seen that obvious differences in both mean and trend between ET_pm and ET_th existed. This mainly resulted from the TH formula only considering the effect of temperature on PET, while the change of PET in the Poyang Lake basin was the result of multiple factors, and the net solar radiation and wind velocity were the main factors for this change [54,55]. As such, the PM method considered the thermal and aerodynamic factors, in which the thermal factor played a major role in spring and summer, and aerodynamic factors gradually dominated in autumn and winter [18].

In order to further explore the relationships between precipitation, PET, and SPEI_th/SPEI_pm in the Poyang Lake basin, the correlation analysis was conducted. Table 4 shows that the SPEI_th and SPEI_pm had approximate correlations with the precipitation, and significant positive correlations were detected between precipitation and SPEI_th/SPEI_pm. Meanwhile, for both SPEI_th and SPEI_pm, the correlations with the precipitation were generally higher, with the correlation coefficients above 0.95. This indicates that precipitation was the decisive factor in the SPEI index. As for PET, negative correlations were detected between PET and SPEI_th/SPEI_pm. Statistically significant negative correlations existed between SPEI_pm and ET_pm, and the correlation between SPEI_pm and ET_pm on both an annual scale and seasonal scales was above −0.70. Comparatively, the correlation of SPEI_th and ET_th was relatively lower, ranging from −0.17 to −0.65, especially for winter, in which it was only −0.1766.

Table 4. The correlation coefficients between climatic factors and SPEI_th/SPEI_pm in the Poyang Lake basin.

Climatic Factor	Spring		Summer		Autumn		Winter		Year	
	SPEI_pm	SPEI_th	SPEI_pm	SPEI_th	SPEI_pm	SPEI_th	SPEI_pm	SPEI_th	SPEI_pm	SPEI_th
Precipitation	0.9920	0.9896	0.9839	0.9826	0.9652	0.9637	0.9822	0.9793	0.9903	0.9883
ET_pm	−0.7285		−0.8443		−0.7484		−0.7803		−0.7898	
ET_th		−0.4766		−0.6481		−0.3522		−0.1766		−0.3981

Comparing Figures 2 and 7, it could be found that the values of SPEI_th and SPEI_pm were quite similar, although the accumulated values of ET_pm and ET_th on an annual scale or seasonal scales had obvious differences. In addition, the correlations of SPEI_th and SPEI_pm on an annual scale and seasonal scales were above 0.97, much higher than that of ET_pm and ET_th between 0.31 and 0.77. The results are generally consistent with previous studies [20,31], revealing that the method for PET calculation was not critical to change in wetness and dryness conditions.

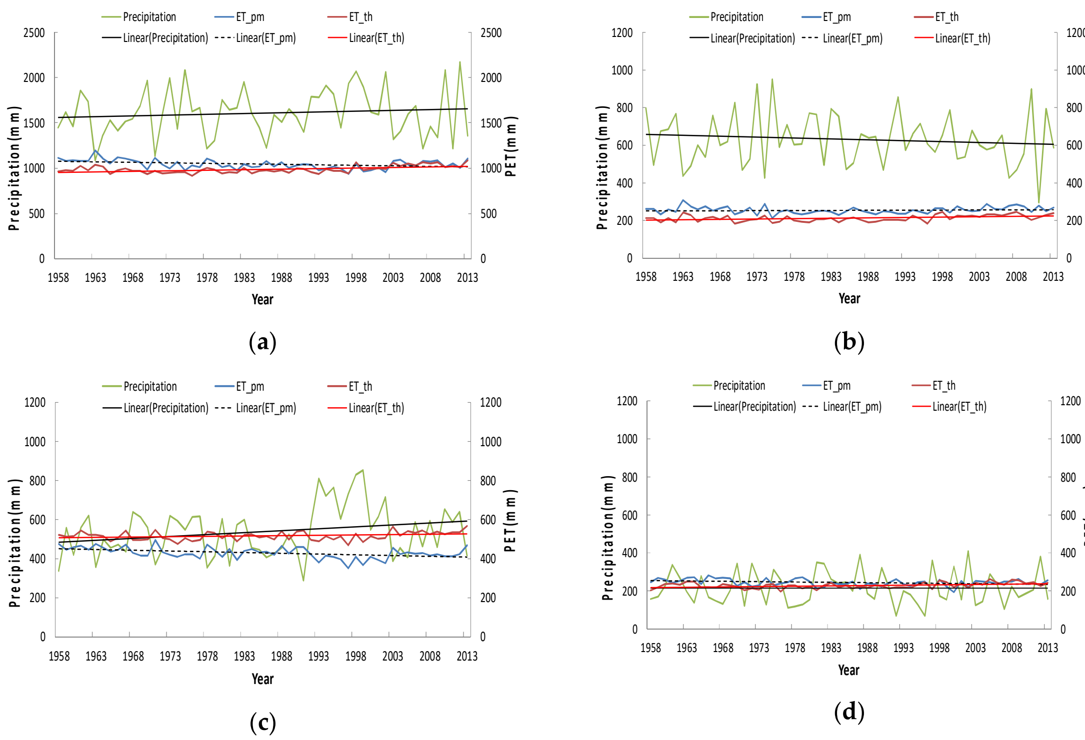
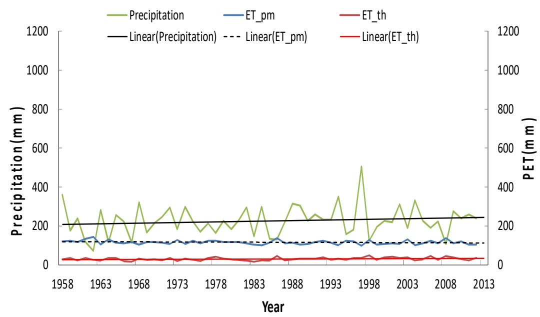


Figure 7. *Cont.*



(**e**)

Figure 7. Changing trends of annual (**a**), spring (**b**), summer (**c**), autumn (**d**), and winter (**e**) precipitation and PET in the Poyang Lake basin during 1958–2013.

3.3.3. Applicability of the SPEI_pm and SPEI_th in Poyang Lake Basin

To analyze the difference between SPEI_pm and SPEI_th on an annual scale as well as seasonal scales to understand the relationship between SPEI_pm and SPEI_th, the conditional probability of SPEI_pm and SPEI_th was used to measure the probability of a given drought or wet event 'A' when another drought or wet event 'B' has occurred, in which A and B were the drought or wet events identified from SPEI_pm and SPEI_th, respectively. Here, we set −1.0 as the threshold value for the drought condition and 1.0 for the wet condition, therefore, drought events were assumed from the probability of SPEI_pm (<−1.0) or SPEI_th (<−1.0). Meanwhile, wet events were assumed from the probability of SPEI_pm (>1.0) or SPEI_th (>1.0). Table 5 listed the conditional probability of the drought or wet events from SPEI_pm and SPEI_th on an annual scale and seasonal scales in the whole Poyang Lake basin from 1958 to 2013.

Table 5. Conditional probability of SPEI_pm (A) and SPEI_th (B) on an annual scale and inter-seasonal scales.

Conditional Probability	P(B|A)		P(A|B)		P(C|A)		P(A|C)	
	Wet	Drought	Wet	Drought	Wet	Drought	Wet	Drought
Spring	0.97	0.92	0.97	0.96	0.87	0.79	1.00	0.95
Summer	0.93	0.92	0.96	0.88	0.93	0.84	1.00	0.91
Autumn	0.97	0.87	1.00	0.87	0.97	0.84	0.93	0.96
Winter	0.91	0.96	0.97	0.88	0.82	0.96	1.00	0.96
Year	0.94	0.91	0.97	0.90	0.89	0.86	0.98	0.95

Notes: C is the drought or wet events identified from SPI.

According to Table 5, almost all droughts identified using the SPEI_pm (SPEI_th) were also identified as droughts with the SPEI_th (SPEI_pm). Meanwhile, compared to the identified drought condition, SPEI_pm (SPEI_th) could preferably also detect a wet condition that was identified with SPEI_th (SPEI_pm). For instance, the probability of the drought event where the spring SPEI_th was below −1.0, P(B|A), was 0.92 under the condition where the spring SPEI_pm was below −1.0. In contrast, the P(A|B) for spring SPEI_pm (<−1.0) given by spring SPEI_th (<−1.0) was 0.96. These results indicate that whether it was under the condition of droughts identified using the SPEI_pm or under the condition of droughts identified by the SPEI_th, each of them could have a greater chance of detecting droughts that were identified by another index. Similar results could easily be found in detecting a wet condition. For example, the P(B|A) for spring SPEI_th (>1.0) given by spring SPEI_pm (>1.0) was 0.97, while P(A|B) for spring SPEI_pm (>1.0) given by spring SPEI_th (>1.0) was 0.97. These meant that both SPEI_pm and SPEI_th could better detect wet events that were identified by SPEI_pm or SPEI_th. In other words, SPEI_th could identify a drought or wet condition that was detected with SPEI_pm within the same historical period.

3.4. Comparison between SPI and SPEI for Dry/Wet Variations

According to the above analysis results, in which precipitation was a dominant factor to determine change in the dry and wet conditions in the Poyang Lake basin, we wondered whether there was difference between SPI and SPEI in the basin. For this reason, the SPI was calculated and a comparative analysis of two drought indexes was conducted. Here, we took SPEI_pm as an example for comparative analysis.

Table 3 showed the MK trends of the SPI series on an annual scale and seasonal scales in the whole Poyang Lake basin from 1958 to 2013. From Table 3, it could be found that a wetting trend was detected in the watershed in both the SPEI_pm and SPI series on an annual scale as well as seasonal scales during the period 1958–2013, except for spring and autumn, and the trend of the former was more obvious than the latter. A drying trend was observed in the SPEI_pm and SPI series in spring. In autumn, the dry and wet conditions in the SPEI_pm and SPI series had opposite trends. There was a wetting trend in the autumn SPEI_pm series, but a drying trend in the autumn SPI series. In addition, as shown in Figure 5, the frequency of drought based on SPI in the whole basin was 14.0%, and the frequency of wet episodes based on SPI was 16.4%. Compared to the SPEI_pm, the frequency of the drought or wet events identified by SPI was slightly lower on seasonal scales as well as annual scale in the Poyang Lake basin during the period 1958 to 2013, although the frequency of the drought or wet events identified by both SPEI_pm and SPI was almost the same. Also, the occurrence of the normal state was more frequent in the SPI than in SPEI_pm in the Poyang Lake basin during the period 1958 to 2013.

Generally, these results show that the pattern of variations in the SPI series were consistent with those in the SPEI_pm series. To explain the reason behind this, the coefficients of variation of precipitation and PET in the Poyang Lake basin during the period 1958 to 2013 were calculated, which were 0.165 and 0.048, respectively. Considering that SPEI was calculated from the difference between precipitation and PET, and the range of precipitation change (reflected by variation coefficient of precipitation) was much larger than that of PET change (reflected by variation coefficient of PET), the change in SPEI was dominated by the precipitation change, which determined change in the dry and wet conditions. The results here generally concur with Wang et al. and Jiang et al. [25,56]. Wang et al. indicted that the change of SPEI_pm was dominated by precipitation change, which made SPEI_pm generally in agreement with SPI [56]. Jiang et al. argued that the correlations between SPEI and SPI were detected to be relatively high on all time scales, which indicated that precipitation was the main explanatory variable of drought severity [25]. However, Ye et al. indicated that in addition to the effect of precipitation, the impact of temperature anomaly on the dry/wet variability may not be neglected. The contribution of increased temperature to the drought intensity of the Poyang Lake basin for the typical drought years of 2003, 2007, and 2009, was about 22.8%, 9.1%, and 23.9%, respectively [53]. Li et al. also found that the apparent differences between the SPI and the SPEI series in the upstream regions of Yangtze River Basin were mainly due to the changes in air temperature. This result indicated that if the influence of temperature on drought conditions was neglected, it may bring a large error to the estimation [57]. Consequently, although precipitation was a dominant factor to determine change in the dry and wet conditions, in some areas and seasons, potential evapotranspiration may play a modulating role in wet and dry changes, which made the above differences between the SPEI and the SPI.

To further analyze the difference between SPEI_pm and SPI on an annual scale as well as seasonal scales, the conditional probability of SPEI_pm and SPI was calculated (Table 5). It could be found from Table 5 that under a drought or wet condition identified by the SPI, the probability of the drought or wet event detected by SPEI_pm, P(A|C), was above 0.90. In contrast, under a drought or wet condition identified using the SPEI_pm, the probability of the drought or wet event detected by SPI, P(C|A) was smaller than P(A|C). This means that SPEI_pm had a greater chance of detecting a drought or wet condition that was identified by SPI within the same historical period. Therefore, because of considering both precipitation and evapotranspiration, SPEI_pm was more suitable than the SPI to analyze the characteristics of the dry/wet variations under the background of global climate change.

4. Conclusions

In this study, SPEI was applied to characterize the dry and wet conditions in the Poyang Lake basin from 1958 to 2013. As two representative parameterizations for PET calculation, the PM equation and the TH equation were both employed to obtain two types of SPEI. The annual and seasonal variations in dryness and wetness by two SPEIs and their differences in the Poyang Lake basin were analyzed. The main conclusions are summarized as follows:

1. Both SPEI_pm and SPEI_th showed a trend of humidification in the Poyang Lake basin on an annual scale as well as seasonal scales, except for spring and autumn during the period 1958–2013. A drying trend was observed in the spring. Considering the importance of spring for crop growth, the drying trend in spring might have an impact on crop yields. In autumn, the changes of dry and wet conditions in two SPEIs had opposite trends. However, all trends from two SPEIs were not significant, while in summer, the increasing trend from SPEI_pm was more significant throughout the whole season.
2. From the spatial perspective, the whole Poyang Lake basin was mainly dominated by the wetting tendency in the annual scale. Almost all the meteorological stations were characterized by increasing trends in summer and winter, especially for the summer SPEI_pm. A few stations in the central and northeast Poyang Lake basin were characterized by non-significant increasing trends, which indicated that a wet tendency dominated the Poyang Lake basin in summer. A drying trend was observed in almost all the stations in spring, which indicated that a dry tendency dominated the Poyang Lake basin in spring, although the trends were not significant at the 95% confidence level. When using the SPEI_pm to detect the trends in autumn, almost two-thirds of the meteorological stations were characterized by increasing trends, whereas all the stations were characterized by decreasing trends in autumn when using the SPEI_th.
3. The highest frequency of dry episodes occurred in autumn, with a frequency of 17.6%, and then followed by about 15% in winter. For wet episodes, the most frequent occurrence was in winter, varying from 18% to 20%, and the second-highest frequency occurred in spring, with the same frequency of 18.8%. Overall, the frequencies of dryness and wetness of different categories calculated from SPEI_pm were consistent with those from SPEI_th, but compared to the SPEI_th, the occurrence of wet episodes was more frequent in the SPEI_pm on the seasonal scale as well as annual scale in the Poyang Lake basin during 1958 to 2013.
4. Significant positive correlations were detected between precipitation and SPEI_th/SPEI_pm, with the high correlation coefficients above 0.95, whereas negative correlations were detected between PET and SPEI_th/SPEI_pm, with the correlation coefficients ranging from −0.17 to −0.85, and the correlation of SPEI_pm and ET_pm was stronger than that between SPEI_th and ET_th. This study revealed that although precipitation was a dominant factor to determine change in the dry and wet conditions in our study area, PET may play a modulating role in wet and dry changes in the Poyang Lake basin, which made the differences between the two SPEIs. On the other hand, despite the obvious differences between ET_pm and ET_th, trends in the SPEI_pm series were generally consistent with those in the SPEI_th series, revealing that the method for PET calculation was not critical to the change in dry/wet conditions.
5. Furthermore, the results of the conditional probability of SPEI_pm and SPEI_th showed that both SPEI_pm and SPEI_th could better detect wet or dry events that were identified by SPEI_pm or SPEI_th. In other words, SPEI_th could identify a drought or wet condition that was detected with SPEI_pm within the same historical period. Therefore, SPEI_th is basically feasible for analysis of wetness and dryness in the Poyang Lake basin, where meteorological data is scarce.

Nevertheless, in this study, the preliminary analysis of variability of dry/wet conditions and comparative analysis of two SPEIs were carried out in the Poyang Lake basin for the period of 1958–2013. Considering the complexity of variations in dryness and wetness, the mechanisms of these changes remain unclear. Therefore, further work can be focused on sensitivity analysis of the dry/wet variations to different meteorological factors to better understand the changes of dry/wet conditions in the Poyang Lake basin. In addition, the relationship between river discharge and SPEIs based on different PETs estimated on multiple time scales should be examined in the future research to verify the potential usefulness of SPEIs for dry/wet condition monitoring.

Author Contributions: All authors were involved in designing and discussing the study. W.L. undertook the data analysis and drafted the manuscript. L.L. revised the manuscript and edited the language. All authors have read and approved the final manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

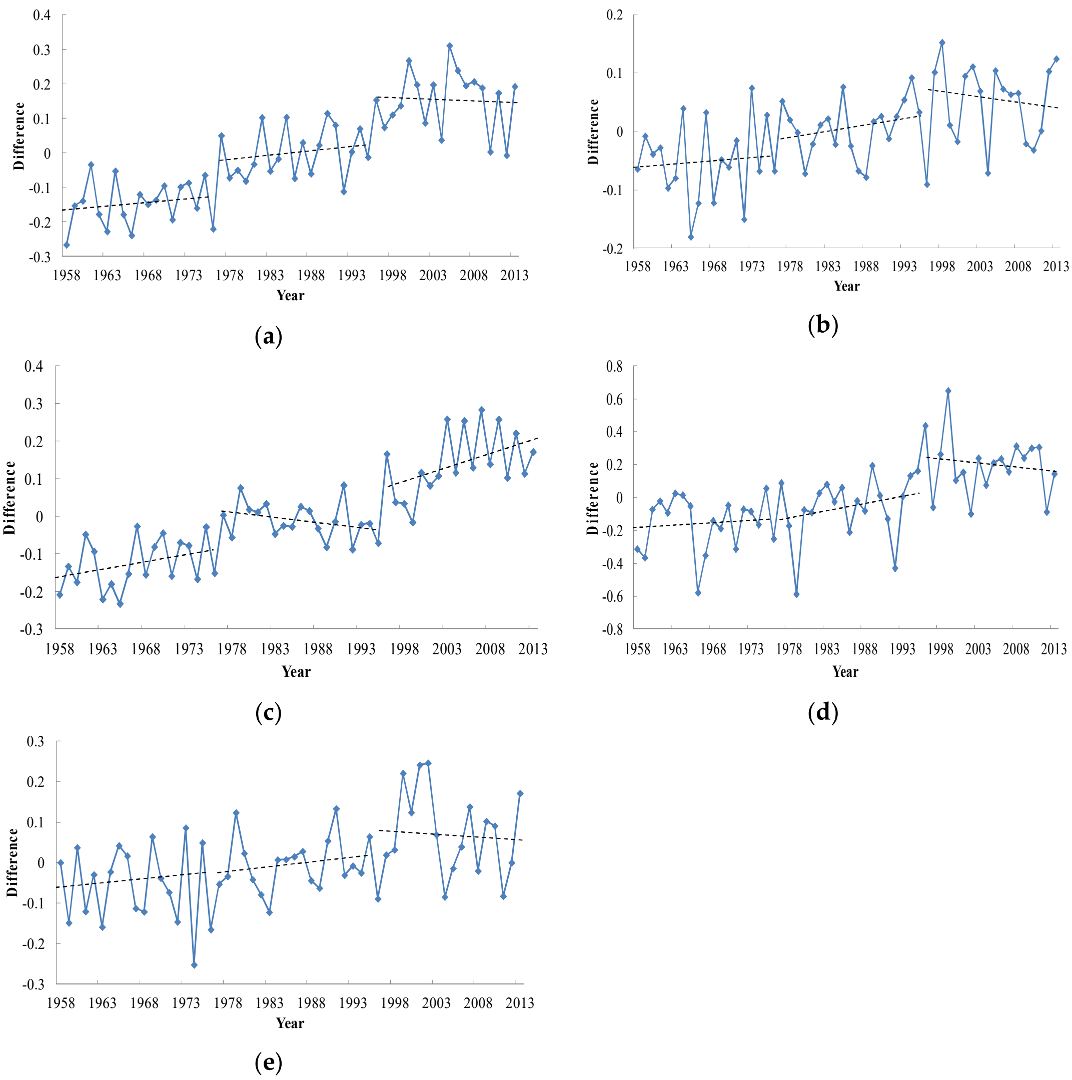

Figure A1. Differences between averaged annual (**a**), spring (**b**), summer (**c**), autumn (**d**), and winter (**e**) SPEI_pm and SPEI_th in the Poyang Lake basin during 1958–2013.

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