Similarity, difference and correlation of meteorological and hydrological drought indices in a humid climate region – the Poyang Lake catchment in China

Xuchun Ye, Xianghu Li, Chong-Yu Xu and Qi Zhang

ABSTRACT

Based on the estimation of standardized precipitation–evapotranspiration index (SPEI) and standardized runoff index (SRI), this study investigated the variability and correlation of hydrological drought and meteorological drought in a humid climate region – the Poyang Lake catchment in China. Results indicate that the occurrences of hydrological droughts in the catchment are different from those of meteorological drought on both a seasonal and annual basis. However, annual variability of both indices showed the same periodic variation characteristics during the study period. With comparison of the performance of SPEI and SRI time series at different timescales, our observation reveals that the two drought indices show a higher degree of similarity and correlation as timescales increased. In addition, SRI is found to be less variable than SPEI at shorter timescales and it shows an obvious hydrologic delay of about 1–2 months in response to SPEI at timescales >12 months. Due to hydrologic detention of subsurface soil moisture, shallow groundwater and perhaps reservoir storage, a 2-month timescale of SPEI is found to be more appropriate for river discharge monitoring, especially for those rivers with similar drainage area, climate and geographical conditions as in this study region.

Key words | drought variability, hydrological drought, meteorological drought, Poyang Lake catchment

Xuchun Ye
School of Geographical Sciences,
Southwest University,
Chongqing 400715,
China

Xianghu Li
Qi Zhang (corresponding author)
Key Laboratory of Watershed Geographic Sciences,
Nanjing Institute of Geography and Limnology,
Chinese Academy of Sciences,
Nanjing 210008,
China
E-mail: *qzhang@niglas.ac.cn*

Qi Zhang
Key Laboratory of Poyang Lake Wetland and Watershed Research, Ministry of Education,
Jiangxi Normal University,
Jiangxi 330000,
China

Chong-Yu Xu
Department of Geosciences,
University of Oslo,
Oslo,
Norway
and
Department of Earth Sciences,
Uppsala University,
Sweden

INTRODUCTION

Variability of water resources has become a serious issue facing many communities and nations around the world within the background of global climate change. It is reported that the well-evidenced global warming over the last century has seriously altered hydrological regimes at regional to global scales, resulting in more and more severe floods and droughts all over the world (Huntington 2006; Jung *et al.* 2012; Xiong *et al.* 2013; Gosling 2014; Emam *et al.* 2015; Yan *et al.* 2016). This situation looks to continue at present and in the near future according to the report of IPCC (2013). Although public awareness of extreme climatic events has risen sharply and significant progress in science and technology for environmental management has been achieved during the past decades, our society still continues to suffer from the consequences of these meteorological and hydrological hazards worldwide (e.g., Nafarzadegana *et al.* 2012; Tao *et al.* 2013). From a scientific and practical point of view, understanding the changing characteristics of drought and wetness variations is of essential importance for improving integrated water resources management at the catchment scale and human mitigation of hydrological alterations.

Drought is a natural phenomenon of near surface water shortage caused by regional moisture deficit or unbalance of water supply and demand in a region during a certain period of time. This phenomenon is usually considered as a

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common, widespread, and recurring climate-related hazard and can occur virtually in all climate zones (Riebsame *et al.* 1991; Moradi *et al.* 2011; Portela *et al.* 2015). Due to complex underlying causes and different perspectives that have been focused on, drought classification and monitoring methods are usually not consistent. Commonly, environmental drought generally includes (1) meteorological drought, (2) hydrological drought, (3) agricultural drought, and (4) socio-economic drought (Heim 2002). However, the first two are most attractive to scientists and researchers. Meteorological drought is the basic precondition for the other types of environmental drought, and usually defines a precipitation deficit over a region for a period of time. Hydrological drought is the result of long-term meteorological drought, which is characterized by the quick decrease of stream flow or the abnormal low stage of river or lake water level. Drought not only directly affects people's water security and food security; continuous drought may also change surface landscapes (such as land cover and soil properties), and further affects the processes of runoff yield and flow concentration, causing a series of ecological environmental problems (Weng & Yang 2010). As the occurrence of drought hazard is not unexpected, research on the occurrence and development processes of drought should be given sufficient attention.

In order to quantitatively study the intensity and duration of drought events, various drought indices have been developed over the past few decades (Palmer 1965; McKee *et al.* 1993; Heim 2002; Rahmat *et al.* 2015; Zhang *et al.* 2015; Zhu *et al.* 2016). The Palmer drought severity index (PDSI) (Palmer 1965) and standardized precipitation index (SPI) (McKee *et al.* 1993; Rahmat *et al.* 2013) are the two typical indicators for assessing the conditions of meteorological drought. Calculated from a simple water–balance model forced by monthly precipitation and temperature data (Palmer 1965), the PDSI is effectively applied in large-scale drought assessments (Sheffield *et al.* 2012). However, lack of multi-scalar character makes the PDSI an unreliable index for identifying different types of drought (Sheffield *et al.* 2012; Tao *et al.* 2013). The SPI has been widely used to reveal meteorological drought and was proven to be a useful tool in the estimation of the intensity and duration of drought events (Bordi *et al.* 2004; Zhang *et al.* 2009; Nafarzadegana *et al.* 2012). The SPI calculation is based only on precipitation deficiency, but neglects other critical variables that may affect drought conditions. Therefore, it is not an ideal tool for drought assessment in those areas with obvious climate change. For those reasons, Vicente-Serrano *et al.* (2010) proposed a new drought index: the standardized precipitation–evapotranspiration index (SPEI) based on precipitation and potential evapotranspiration, which effectively combines the physical principles of the PDSI with the multi-scalar character of the SPI, and has become widely used in recent years.

With respect to meteorological conditions, river discharge directly reflects the amount of water resources in a region that may have impacts on local society. For the assessment of hydrological drought, several indices have been developed, including Palmer hydrological drought severity index, surface water supply index, and standardized runoff index (SRI), etc. (Shukla & Wood 2008; Marengo *et al.* 2011). Among these, the SRI is a natural extension of SPI used to describe the anomalies of stream flow and river or lake stage. It, however, has more appeal than the SPI as it incorporates hydrological and meteorological processes that influence the volume and timing of streamflow. Due to the effects of underlying landscape conditions as well as human activities, the variation of hydrological drought index may be desynchronized from the response of meteorological drought index.

Assessment of the variability of hydro-meteorological drought in a region is essential for local water resources management and for the prevention of the risk of natural hazards. In addition, understanding the characteristics of different drought indices will provide insight into the causes and impacts of different indices. As a consequence of climate change, seasonal hydro-meteorological drought has occurred more frequently in recent decades, even in humid regions. Associated with this context, the main goals of this study are: (1) to evaluate the potential capability and performance of SPEI and SRI in assessing drought variability; and (2) to examine the correlation and differences between hydrological droughts and meteorological droughts at different timescales.

STUDY REGION AND DATA

The Poyang Lake catchment is surrounded by a series of low mountains and hills in the east, south, and west, and covers an area of 162,200 km^2. The lake receives water mainly from five tributary rivers: Ganjiang River, Xiushui River, Fuhe River, Raohe River, and Xinjiang River (see Figure 1(a)), and then discharges into the Yangtze River in the north. As a typical open water-carrying lake that naturally connects to the Yangtze River, the occurrence of droughts and floods in the lake is not only controlled by the Yangtze River discharge, but is also highly affected by the catchment inflows (Hu *et al.* 2007; Zhang *et al.* 2014; Li *et al.* 2015). Change of catchment inflow is one of the important influencing factors that has caused the frequent occurrence of flood and drought in the lake in recent years.

The catchment belongs to a subtropical climate zone with an average annual temperature of 17.5 °C and average annual precipitation of 1,665 mm (Figure 1(b)). Due to the dominant effect of the Southeast Asian Monsoon, 45% of annual precipitation is concentrated in the flood season from April to June (Figure 1(b)).

In this study, a complete data set of daily precipitation and temperature from 14 standard national weather stations inside the catchment was obtained from the National Climate Centre of China Meteorological Administration (CMA). The data set of all weather stations covers the period 1960–2010 with no missing data on the variables. Data quality control was done by CMA before delivery. Locations of these weather stations can be referred to in Figure 1.

Observed daily stream flows for 1960–2010 at five gauging stations (Figure 1) were collected from the Hydrological Bureau of Jiangxi Province, China. The drainage area of the five gauging stations accounts for 74.5% of the total Poyang Lake catchment. Among the five stations, Waizhou, Lijiadu, and Meigang located at the lower reaches of the Ganjiang, Fuhe, and Xinjiang Rivers were considered as the outlet for these sub-catchments. Dukengfeng and Wanjiabu are the two stations with relative small drainage areas and are located at the branches of the Raohe and Xiushui rivers. The basic features of these gauging stations are listed in Table 1.

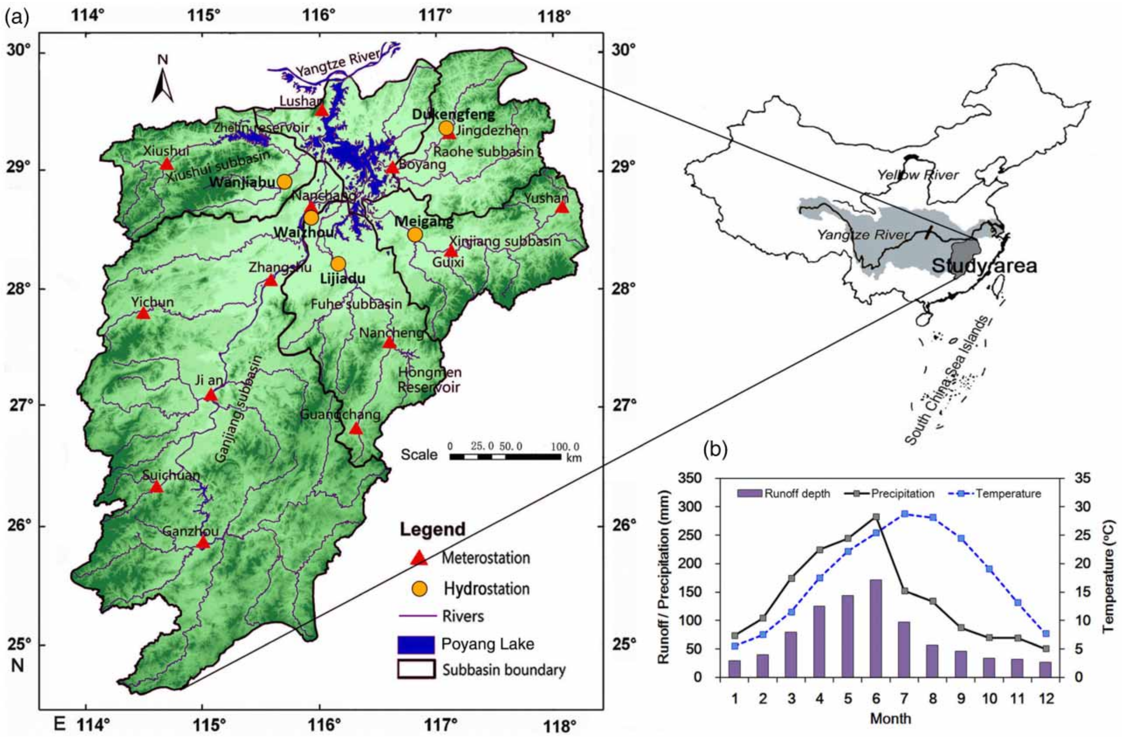

Figure 1 | Location and hydro-meteorological condition of Poyang Lake, China. (a) Distribution of hydrological and meteorological stations across the catchment and (b) mean monthly precipitation, temperature and runoff depth of the catchment for 1960–2010.

Table 1 | List of hydrological gauging stations used in this study

Gauging station	Location	Coordinates	Gauged area (km^2)	Average annual runoff depth (mm)
Waizhou	Ganjiang	(115.83°, 28.63°)	80,948	844
Lijiadu	Fuhe	(116.17°, 28.22°)	15,811	806
Meigang	Xinjiang	(116.82°, 28.43°)	15,535	1,157
Dufengken	Changjiang tributary of Raohe	(117.12°, 29.16°)	5,013	927
Wanjiabu	Liaohe tributary of Xiushui	(115.65°, 28.85°)	3,548	984

METHODS

Meteorological drought index – SPEI

Although there are several methods for meteorological drought estimation, the SPEI was selected to estimate meteorological drought in this study because it combines the physical principles of the PDSI with the multi-scalar character of the SPI (Tao *et al.* 2013). The process of SPEI estimation is completely consistent with SPI, but adds the effect of potential evapotranspiration.

In this method, the calculation of monthly climatic water balance is given as:

$$D_i = P_i - PET_i \tag{1}$$

where P_i is precipitation for the month i and PET_i is potential evapotranspiration for the month which is calculated by the Thornthwaite method (Thornthwaite 1948), D_i is the difference of the two variables.

Different timescales of the water deficit time series can be established as:

$$D_n^k = \sum_{i=0}^{k-1} (P_{n-i} - PET_{n-i}), \quad n \geq k \tag{2}$$

where k is timescale (month), and n is the length of data series.

The probability density function of a three parameter log-logistic distribution for the established data series is expressed as:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \tag{3}$$

where α, β, and γ are scale, shape, and origin parameters, respectively, which can be obtained by the L-moment method. The cumulative probability at a given timescale is calculated as:

$$F(x) = \int_0^x f(x)dt = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \tag{4}$$

After transforming the cumulative probability to standard normal distribution, the SPEI can be calculated as follows:

$$\mathrm{SPEI} = W - \frac{C_0 + C_1 + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \tag{5}$$

$$W = \sqrt{-2\ln(P)} \quad P \leq 0.5 \tag{6}$$

where $P = 1 – F(x)$. When $P > 0.5$, then P is replaced by $1–P$. The constants are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$ and $d_3 = 0.001308$.

According to the value of SPEI, meteorological drought can be classified into three categories (Vicente-Serrano *et al.* 2010). Table 2 lists the SPEI classification and corresponding cumulative probabilities of drought occurrences. More detailed information can be referred to in Vicente-Serrano *et al.* (2010) and Tao *et al.* (2013).

Table 2 | Meteorological drought according to SPEI classification

Category	SPEI
Normal	$-1.0 < \mathrm{SPEI} < 1.0$
Moderate dry	$-1.5 < \mathrm{SPEI} \leq -1.0$
Severe dry	$-2.0 < \mathrm{SPEI} \leq -1.5$
Extreme dry	$\mathrm{SPEI} \leq -2.0$

Hydrological drought index – SRI

The concept employed by McKee *et al.* (1993) for SPI was applied in defining SRI. The calculation of SRI follows the same procedure as for SPI, but the input for this index is monthly runoff data rather than monthly precipitation. The fundamental idea of using SRI is to examine drought from a hydrological perspective with comparison to traditional drought indices, such as SPI and PDSI. In addition, the SRI has the same classification as that of SPI.

Trend test

In this study, the nonparametric Mann–Kendall (MK) statistical test was applied to estimate the change trend of seasonal hydro-meteorological drought. The method is widely used for trend detection in hydrological and meteorological series due to its robustness against non-normal distributions and insensitiveness to missing values (e.g., Wang *et al.* 2008; Zhang *et al.* 2009; Ehsanzadeh & Adamowski 2010; Li *et al.* 2012). The null hypothesis H_0 of the MK test is that there is no trend of the calculated drought conditions from which the data set X (x_1, x_2, x_3 … x_n) is drawn. The null hypothesis H_0 should be rejected if statistic parameter $|Z| \geq 1.96$ at 5% significance level. The Z value is a standard normal variable that represents the significance level of a specific trend. A positive value of Z indicates increasing trend, and a negative value of Z indicates decreasing trend.

The authors of this paper have applied this method in the study of streamflow and climatic series of the Poyang Lake catchment (Ye *et al.* 2013; Zhang *et al.* 2014). Details about the method can be referred to in the above-mentioned literature.

Continuous wavelet transform

The continuous wavelet transform (CWT) is a mathematical method that was developed for signal processing. Through CWT analysis, hydro-meteorological series can be decomposed into time–frequency space to determine both the dominant modes of variability and how those modes vary in time (Torrence & Compo 1998). Up to now, the CWT method has been widely used for analyzing localized variations of power within a geophysical time series (Grinsted *et al.* 2004; Zhang *et al.* 2009). The concept of the method is thoroughly explained and discussed by Torrence & Compo (1998). In this study, as a complement to the MK method which studies the trend of the drought indices, the CWT method was applied to study the periodicity of hydro-meteorological series of the Poyang Lake catchment, and Morlet wavelet was chosen as a basic wavelet because it provides good balance between time and frequency localization.

RESULTS

Frequency of hydro-meteorological drought months

According to SPEI classification, statistical results indicate a total of 105 meteorological drought months occurred in the Poyang Lake catchment during the period 1960–2010. Among these drought months, moderate drought occurred in 70 months, severe drought occurred in 27 months, and extreme drought occurred in 8 months. On a seasonal basis, the highest occurrence of meteorological drought was found in autumn, and followed by winter, summer, and spring (Figure 2(a)). However, the droughts that occurred in autumn were mainly moderate droughts. Extreme droughts mainly occurred in summer. Further investigation indicated that the occurrence of meteorological drought in the Poyang Lake catchment was rather complex, and different categories of dry and wet episodes could occur in any month of a year. For each month, the highest occurrence of meteorological drought was in February, September, and November, and the least was in March and June. Moderate drought mainly occurred in September and November, severe drought mainly occurred in March and October, and extreme drought mainly occurred in May and June (Figure 2(b)). During the past decades, the most intensified meteorological drought occurred in June 1991 with a SPEI value of −2.36. Figure 2(c) indicates that extreme drought mainly occurred in the 1960s, 1990s, and 2000s, with moderate drought and severe drought relatively frequent in the 1970s and 2000s.

By summing the observed streamflow of the five gauging stations, the occurrence of hydrological droughts was also

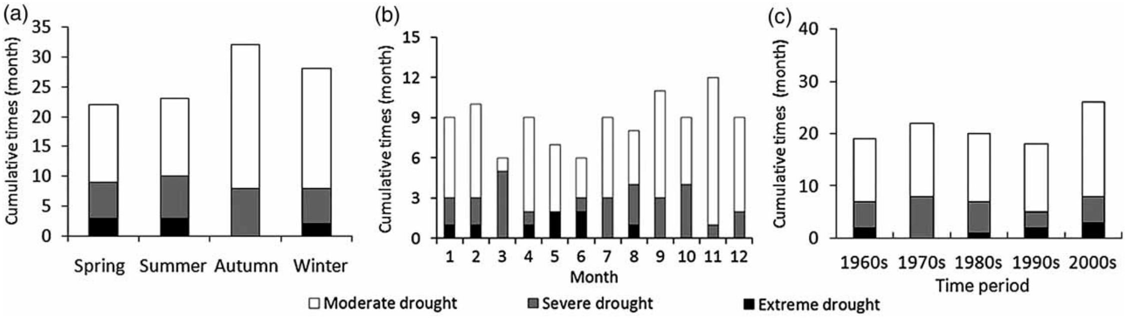

Figure 2 | Cumulative times of meteorological drought of the Poyang Lake catchment for the period 1960–2010: (a) seasonal distribution and (b) decadal distribution.

estimated for the Poyang Lake catchment, and the cumulative frequencies of drought months of different categories were calculated for the study period. As shown in Figure 3, statistical results indicated there were 92 hydrological drought months that occurred in the Poyang Lake catchment during the past 51 years, among which moderate drought occurred in 70 months, severe drought occurred in 15 months, and extreme drought occurred in 7 months. On a seasonal basis, the highest occurrence of hydrological drought was in winter, followed by autumn, summer, and spring. In addition, the droughts that occurred in winter were mainly moderate droughts and extreme droughts mainly occurred in spring (Figure 3(a)). In monthly scale, the highest occurrence of hydrological drought was in February, May, July, and October, while the least was in March and August. Moderate drought mainly occurred in July and February, severe drought mainly occurred in March and May, and extreme drought mainly occurred in April and June (Figure 3(b)). Different from the decadal distribution of meteorological drought, Figure 3(c) indicates that the 1960s and 1970s were the two periods that hydrological drought of different category occurred most frequently. The occurrence of hydrological drought in the 1980s and 1990s was less frequent, and then increased in the 2000s.

Variability characteristics of hydro-meteorological drought

The Poyang Lake catchment is climatically characterized by the subtropical monsoon, annual variability of meteorological condition and surface runoff is highly consistent. Thus, we here focused our analysis on the variability characteristics of catchment meteorological drought. Generally, the wavelet power spectra of the SPEI variability of the catchment demonstrate the pronounced inter-annual and decadal cycles of the climate changes (Figure 4). Continuous wavelet power spectrum in Figure 4(a) indicates that energy centers of frequency space are mainly concentrated in 20 to 25 year bands, 5 to 10 year bands and <5 year bands. This observation demonstrates that there exist three possible periodicities for the annual variability of SPEI of the Poyang Lake catchment during the period 1960–2010. According to the result of wavelet variance, it is clear that

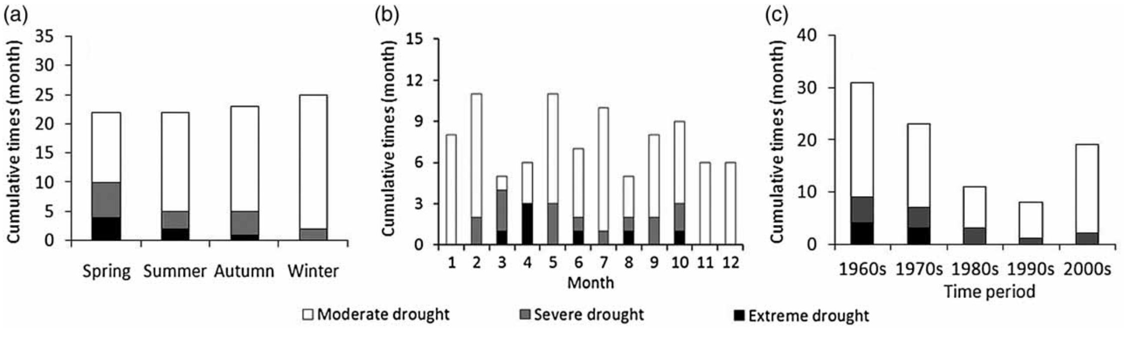

Figure 3 | Cumulative times of hydrological drought of the Poyang Lake catchment for the period 1960–2010: (a) seasonal distribution and (b) decadal distribution. SRI was estimated from the summing streamflow series of the five hydrological stations.

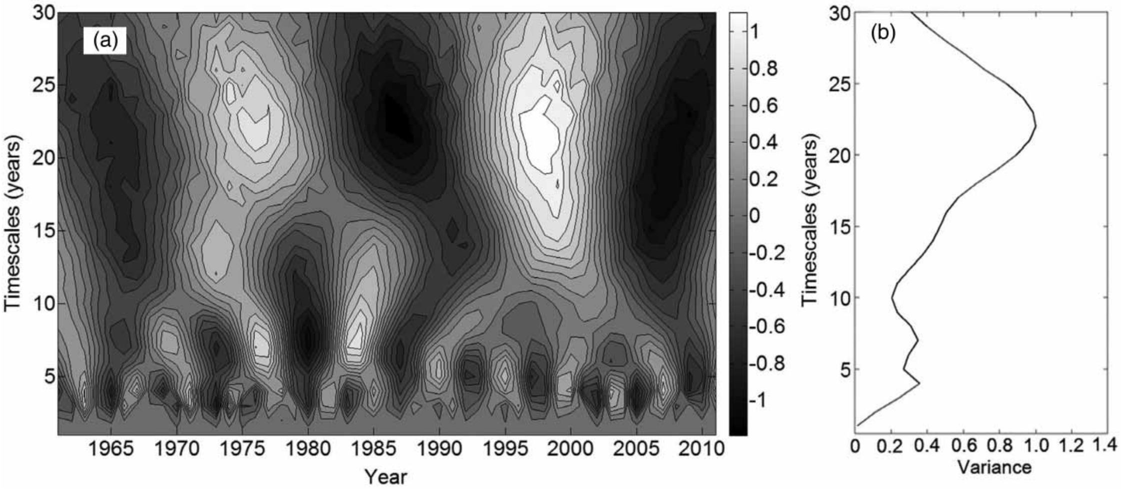

Figure 4 | Periodicity distribution of annual SPEI of the catchment based on Morlet wavelet analysis: (a) continuous wavelet power spectrum and (b) wavelet variance.

the primary periodicity is about 22 years, and the two secondary periodicities are 4 and 7 years, respectively (Figure 4(b)).

On consideration of the distribution patterns of wavelet power spectrum in Figure 4(a), the 22 years primary periodicity of the catchment is remarkably evident. During the study period 1960–2010, the Poyang Lake catchment experienced a periodic evolution process of meteorological drought, wet, drought, wet, and drought. The latest meteorological drought episode began in about 2003, and it is now entering into the later period. According to the distribution of wavelet power spectrum, it seems that the latest drought episode lasted to the end of 2013, and then a wet episode sets in. On the scale of 7 years periodicity, a distinct drought and wet alteration period was found from the middle 1960s to the middle 1980s. However, two distinct drought and wet alteration periods were found on the scale of 4 years periodicity, the first period was from the earlier 1960s to the middle of the 1970s, and the second period was from the earlier 1990s to the middle of the 2000s.

For the long-term change trend of annual hydrometeorological drought, both SPEI and SRI show a slightly increasing trend. However, both increasing trends are not statistically significant (Z values are 0.62 and 0.44, respectively, by MK test). On a monthly basis (as shown in Figure 5(a)), SPEI in March, April, May, September, October, and November shows a decreasing trend. Especially, the decreasing trend in October is relatively obvious, which is close to a 0.05 significance level. In other months, SPEI shows increasing trends, among which, the increasing trends in January and August are relatively obvious and close to a 0.05 significance level. These results

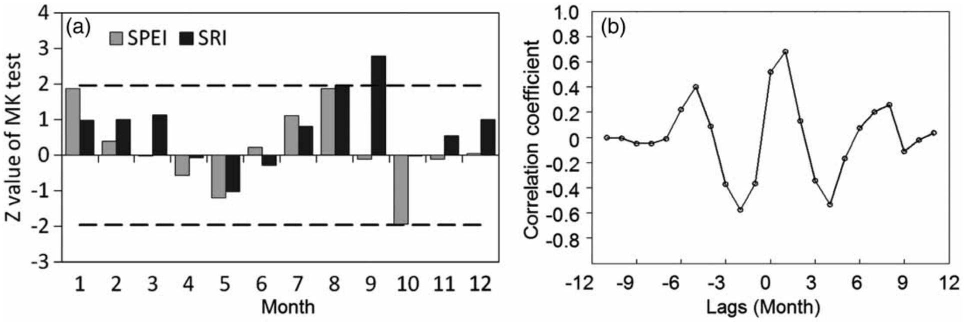

Figure 5 | (a) MK trends test of monthly SPEI and SRI of the catchment. The horizontal dashed lines represent the critical value of 0.05 significance level. (b) Cross correlation between the trends of monthly SPEI and SRI.

indicate that due to seasonal change of local climate, meteorological drought in spring and autumn might be elevated, while in summer and winter it might be alleviated.

Change trend of seasonal SRI is roughly consistent with that of SPEI in January, May, July, and August (Figure 5(a)), but clear differences are seen in other months. A decreasing trend of SRI was mainly found in May and June. In contrast with SPEI, SRI in March, September, and November shows increasing trends. Especially, the increasing trend of SRI in September is significant at a 0.05 significance level. In addition, the increasing trend of SRI in December and February are much more obvious than for SPEI. It is worth noting that according to the change trends of monthly SPEI and SRI, cross-correlation analysis shows that the two indices reach a maximum correlation coefficient at 1-month time lag (Figure 5(b)). This result indicates that changes of hydrological drought in the Poyang Lake catchment are usually delayed for 1 month compared with meteorological drought.

Comparison of SRI and SPEI at different timescales

Figure 6 displays the comparisons of SPEI and SRI for the five different timescales (1, 3, 6, 12, and 48 months) for the years 1960–2010. Undoubtedly, fluctuation and variation of SPEI and SRI series show consistent patterns over the study period. However, the degree of consistency changes with timescales. The statistical result reveals that the correlations between SPEI and SRI drop from 0.95 for the 48-month timescale to 0.91, 0.87, 0.81, and 0.71 for the 12-, 6-, 3-, and 1-month timescales, indicating that the differences between the two indices increase as timescale decreases. Generally, the detention of soil moisture, groundwater or reservoir storages that regulate surface runoff have an impact on SRI, especially for shorter period accumulations in the last two decades. In addition, as reported by Shukla & Wood (2008), given that most effects of hydrologic modulation are limited in a year, the indices with timescales >12 months may not have much influence from current land surface conditions. Due to hydrologic delays in terms of soil moisture, groundwater, and reservoir recharge, the variation of SRI may be desynchronized from the response of SPEI. Results from Figure 6 show that the hydrologic delays begin to be obvious when the timescale is >12 months. Further investigation indicates that the SRI curve is about a 1- to 2-month delay in response to SPEI curve at timescales of 12 and 48 months. The reason for this is that SRI incorporates the land surface dynamics that moderate the hydrologic response, and the delayed recharge of groundwater and reservoir storage would be more obvious at longer timescales.

Relationship of 1-month SRI and SPEI at different timescales

Figure 7 shows the Pearson correlation coefficients between the SPEI series at different timescales (1–12 months) and the SRI at a 1-month timescale. From the figure, it is clear that the correlations of the five stations under different timescales are all positive, but there are important differences with regard to the increase of timescales. Generally, higher correlations are found when SPEI is at shorter timescales. However, the maximum correlation coefficients of the gauging stations are not corresponding to the 1-month timescale of SPEI, but to the 2-month timescale of SPEI. This is particularly obvious for Waizhou, Meigang, Lijiadu, and Dukengfeng stations. Maximum correlation coefficients for the four stations are 0.79, 0.81, 0.78, and 0.75, respectively.

DISCUSSION

The Poyang Lake catchment is one of the most sensitive regions of climate change in the Yangtze River basin; especially the rising temperature and increasing frequency of extreme precipitation have been remarkably obvious since the 1990s (Ye *et al.* 2013). Wang & Chen (2012) pointed out that the impact of temperature anomaly on the drought/wetness variability cannot be neglected. Our recent study, by comparing the performance of SPEI and SPI in the catchment, also concluded that positive temperature anomaly since the 1990s plays an important role that intensifies the drought process, while negative temperature anomaly during 1965–1986 can alleviate droughts (Ye *et al.* 2015). In this study, the estimated frequency distribution of meteorological drought by SPEI reflects well the impacts of both precipitation and

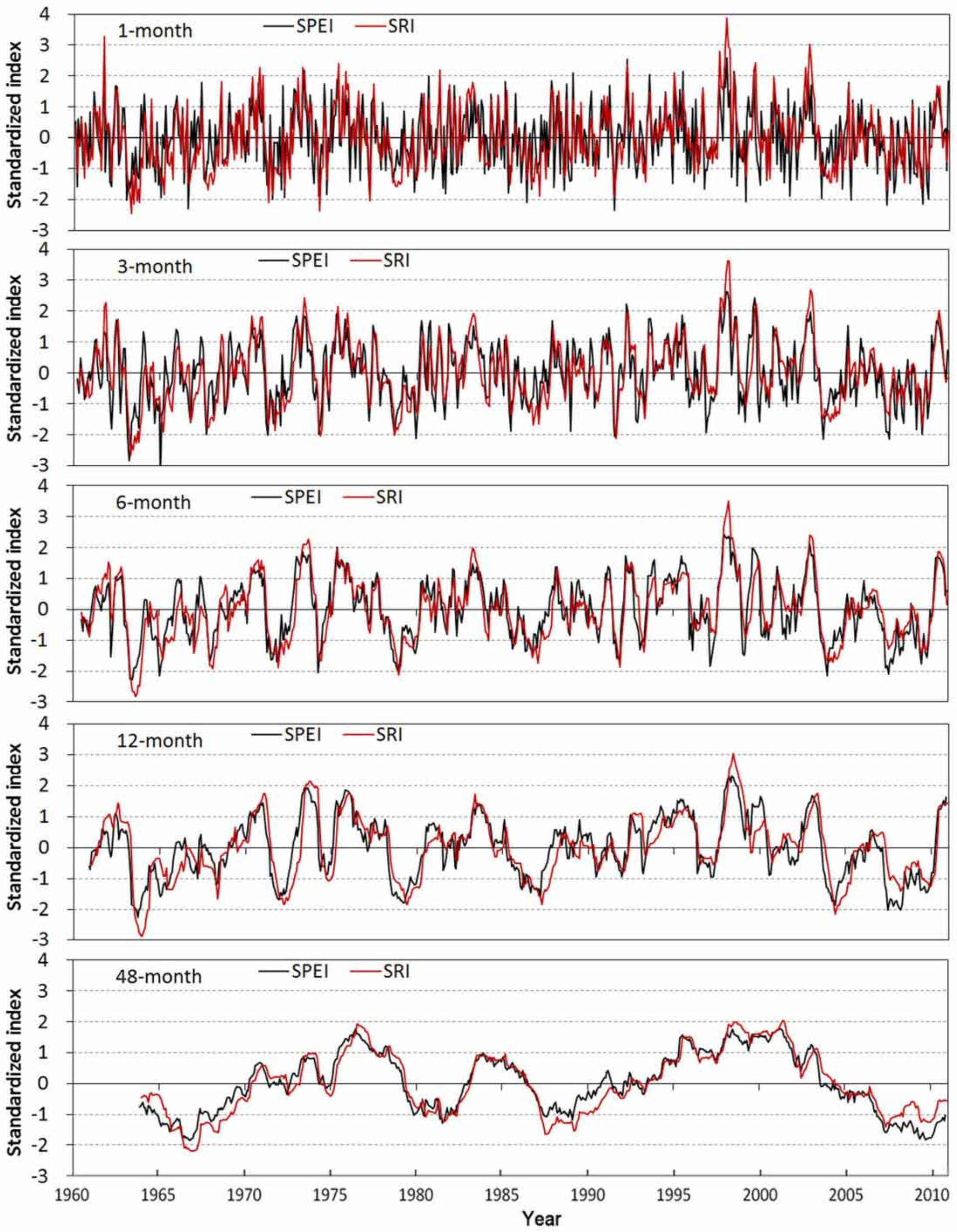

Figure 6 | Historical time series of the SPEI and SRI at 1-, 3-, 6-, 12-, and 48-month timescales. SRI was estimated from the summing streamflow series of the five hydrological stations.

temperature, and the results are somewhat different from those estimations based just on precipitation (e.g., Liu *et al.* 2012b; Min *et al.* 2013). Seasonally, extreme meteorological drought seldom occurs in autumn, while extreme hydrological drought is rare in winter. Min *et al.* (2013) investigated the climatic characteristics of drought in the catchment by using the Z index method, and revealed that extreme meteorological droughts mainly occurred in spring.

On decadal distribution, the occurrences of hydrological drought in the 1960s and 1970s are most frequent, followed by the 2000s. This result is consistent with recent hydrological droughts that have been recorded in the basin. For example, a dramatic decrease of catchment inflow in 2003, 2006–2007, and 2009 may be one of the factors that caused persistent low water levels of Poyang Lake (Min & Zhan 2012). The different occurring frequency of SPEI

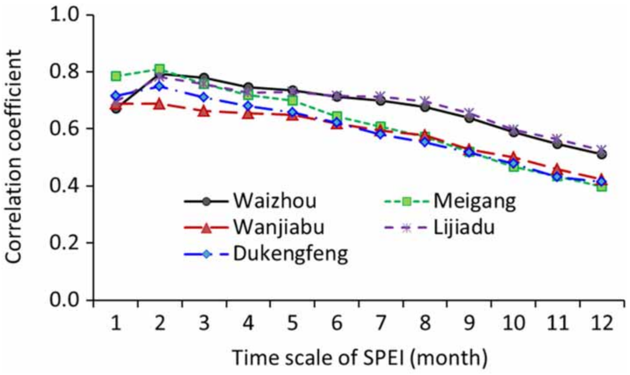

Figure 7 | Correlation of 1-month SRI of five hydrological stations and corresponding gauged catchment SPEI under different timescales. The SPEI of each drainage catchment is calculated by using the averages of observations from the meteorological stations inside the drainage catchment.

(Figure 2(b)) and SRI (Figure 3(b)) can partly be attributed to the changes of underlying landscape characteristics as well as other type of human activities. Similar to many regions in China, the Poyang Lake catchment has undergone intensive human activities in the past decades, including afforestation and deforestation, land reclamation, river regulation, agricultural irrigation and industrial development, etc., which may have exerted considerable impacts on catchment hydrology. Figure 8 shows an obvious increase of forest coverage and total reservoir storage in the Poyang Lake catchment since the end of the 1980s. Although intensified human activities in the catchment have led to a decrease of river discharge on an annual basis in recent years (Ye *et al.* 2013), the effects of increased forest coverage and reservoir storage may considerably modulate the seasonal distribution of river discharge. For example, increased forest coverage may decrease river discharge in the wet season through the increase of evapotranspiration, but increase river discharge in the dry season due to increased groundwater contribution (Guo *et al.* 2008; Ye *et al.* 2011). Similarly, reservoir construction will alter the natural characteristics of river discharge, causing redistribution of river discharge in time and space (Yang *et al.* 2008; Zhang *et al.* 2014). On the basis of the above discussion, it can be concluded that the increases in forest coverage and total reservoir storage in the Poyang Lake catchment since the 1980s could be responsible for the relative alleviated hydrological drought occurring in recent decades by comparison to the elevated meteorological drought.

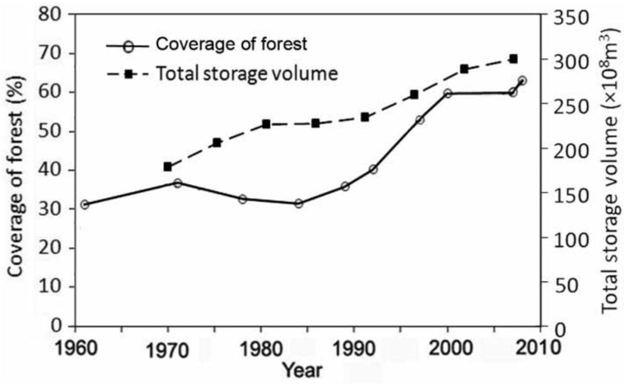

Figure 8 | Changes of forest coverage and total reservoir storage in the Poyang Lake catchment.

As hydrological drought, to a large extent, is the result of long-term meteorological drought, the fluctuations of SPEI and SRI time series at different timescales are somewhat consistent and correlated and the correlation increases as timescales increase. Furthermore, the performance of the SRI series shows an obvious hydrologic delay of about 1–2 months in response to SPEI at timescales >12 months. The desynchronization of the two indices is in agreement with the findings of other studies (e.g., Shukla & Wood 2008; Liu *et al.* 2012a). As is already known, the volume and variation of river discharge are not only determined by the local meteorological conditions, but also affected by the underlying landscape characteristics. The size of the drainage area plays an important role that leads to hydrologic delays in the form of soil moisture, groundwater, and even surface streamflow routines (Raudkiui 1979). The larger the drainage area, the longer the hydrologic delays of soil moisture, groundwater, and streamflow discharges to the catchment outlet. The results of correlation analysis between SRI and SPEI series showed that the maximum correlation coefficient was found between 1-month SRI and SPEI at a timescale of 2 months. This result is consistent with some previous studies, such as those of Vicente-Serrano & López-Moreno (2005) and Du *et al.* (2012), but differs from other studies (e.g., McKee *et al.* 1993; Zhai *et al.* 2010). Of the five gauging stations Lijiadu station has the smallest drainage area, thus river discharge is more associated with the current meteorological conditions than those for other stations. However, for those rivers with relatively larger drainage areas, river discharges are more associated with the current and previous meteorological conditions of shorter periods than of longer periods.

SPEI and SRI in the Poyang Lake catchment showed a primary periodicity of 22 years and two secondary periodicities of 4 and 7 years. This result indicates that on an annual basis, climatic anomalies in the subtropical catchments such as the Poyang Lake catchment are the dominant factor that control the variability of local river discharge. Also, the result of periodicity analysis revealed that the Poyang Lake catchment is now entering into a wet episode. As the change of water resources of the catchment is particularly important for the eco-environmental conservation of the Poyang Lake wetland as well as regional economic development of the lower Yangtze River, outcomes of this study are expected to assist in understanding the medium- and long-term variability of catchment water resources in the near future. Additionally, as the variation of SRI can be desynchronized from the response of SPEI, joint consideration of the relevance of meteorological drought and hydrological drought under various timescales is useful in surface water resources management and hazard protection.

CONCLUSIONS

In this study, the performance of SPEI and SRI in assessing drought variability and the correlation and differences between hydrological droughts and meteorological droughts at different timescales was investigated using hydro-meteorological data from a humid region – the Poyang Lake basin in China. The study concludes that in the Poyang Lake catchment, seasonal hydro-meteorological droughts have occurred frequently in recent decades. Annual variability of both indices showed a primary periodicity of 22 years and two secondary periodicities of 4 and 7 years. SRI is less variable than SPEI at shorter timescales and it shows an obvious hydrologic delay of about 1–2 months in response to SPEI at timescales larger than 12 months. For the desynchronized variation of the two indices at different timescales, the influences of geophysical characteristics of river catchments that moderate the hydrological response should be considered. With respect to the study catchment, the 2-month timescale of SPEI is more appropriate for drought event monitoring, especially for those rivers with drainage areas larger than 0.35×10^4 km^2.

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