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Hydrological drought in two largest river-connecting lakes in the middle reaches of the Yangtze River, China

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ABSTRACT

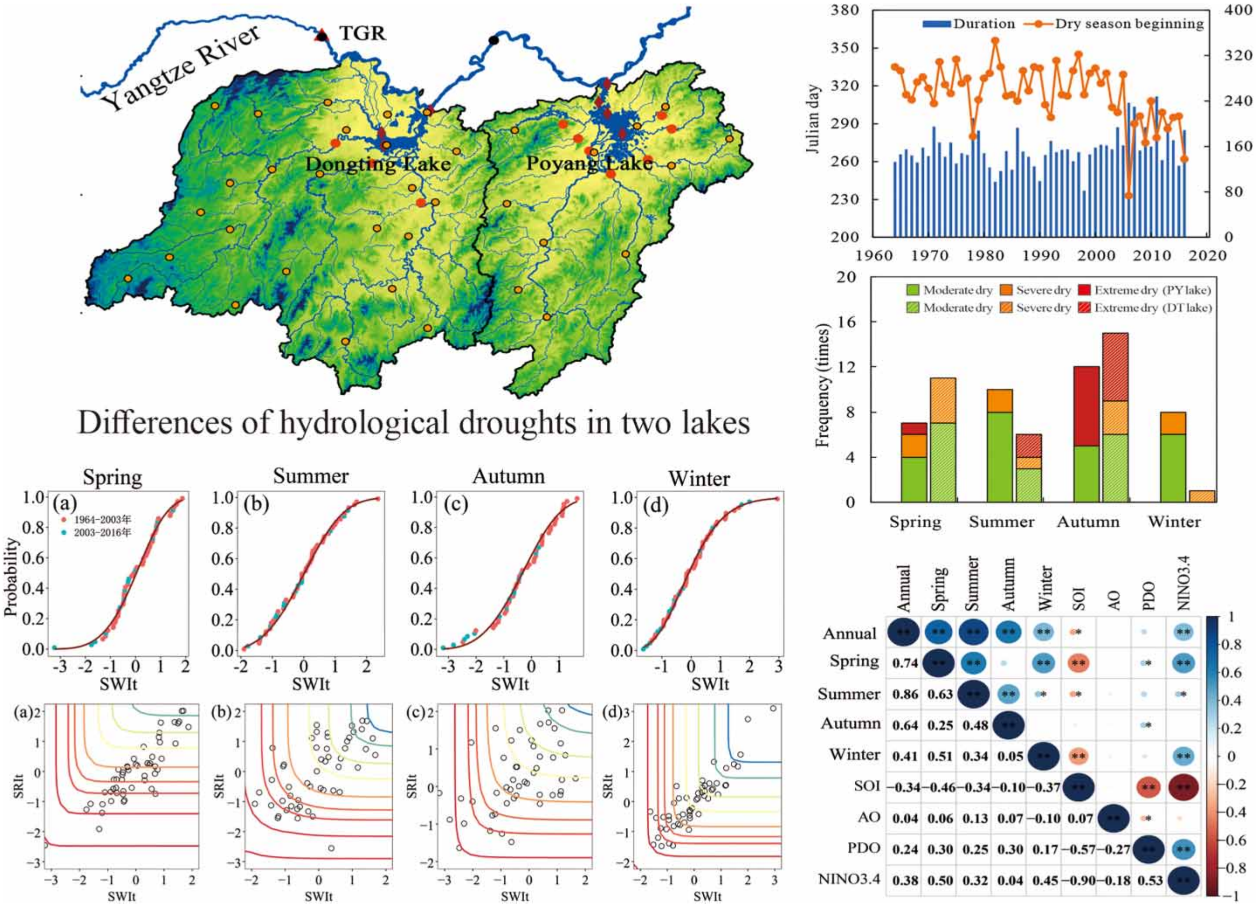
Poyang and Dongting Lakes are two important river-connecting lakes with a complicated water system pattern in the middle reaches of the Yangtze River, China. Recently, extreme drought events occurred frequently in the two lakes. This study analyzed the characteristics and differences of hydrological droughts in Poyang and Dongting Lakes during the period of 1964–2016 and explored the correlation between drought and large-scale climate indices. The results showed that the hydrological droughts of Poyang and Dongting Lakes became increasingly serious. Especially after 2003, both lakes entered the dry season earlier and the intensity of drought was increased. The hydrological drought of Poyang Lake was more serious than that of Dongting Lake in spring (16.40%) and winter (14.26%), while the autumn drought in Dongting Lake (32.46%) was severer than that in Poyang Lake (27.65%). The spring droughts in the two lakes were significantly associated with droughts in their local catchments with the joint probabilities of 10.84 and 9.52%, while the autumn droughts were consistent with the hydrological droughts of the Yangtze River with large joint probabilities (26.39 and 27.76%). The changes in large-scale climate indices more significantly affected the drought in Poyang Lake than that in Dongting Lake, especially in autumn and winter.

Key words: copula, Dongting Lake, hydrological drought, large-scale climate index, Poyang Lake

HIGHLIGHTS

- The average water level of the two lakes in the dry season was lower than that before 2003.
- After 2003, both lakes entered the dry season earlier and the intensity of drought was increased.
- The drought of two lakes in autumn was more consistent with the low water in the Yangtze River.
- The changes in large-scale climate indices more significantly affected the drought in Poyang Lake than that in Dongting Lake.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Drought is among the most common and serious natural disasters that occur worldwide (Wong *et al.* 2013; Chen & Sun 2015). With a global warming background, the frequency and intensity of drought events are increasing significantly, which has become one of the important factors restricting sustainable economic development and social and ecological environments (Vandenberghe *et al.* 2011; Dai 2013; She *et al.* 2013; Song *et al.* 2021). The Yangtze River Basin is one of the areas in China with the most serious drought occurrences due to its complex climatic conditions and a large spatio-temporal variation of precipitation (Dai *et al.* 2008; Zhang *et al.* 2018, 2019; Sun *et al.* 2019; Jiao *et al.* 2020; Li *et al.* 2020). The rapid economic development and the construction of large water conservancy and hydropower projects in the Yangtze River basin further aggravate the drought problem in the region (Guo *et al.* 2012; Sun *et al.* 2012; Wang & Yuan 2018; Ma *et al.* 2019). Statistically, more than 30 hydrological drought events occurred in the Yangtze River basin from 1979 to 2012, and the drought in the middle and lower reaches was more serious than that in the upper reaches (Zhang *et al.* 2019).

Poyang and Dongting Lakes, located in the south bank of the middle reaches of the Yangtze River, are the two largest freshwater lakes in China. Their huge volumes and vast water areas play an important role in water resource supply, ecosystem stability, and industrial and agricultural production (Zhang *et al.* 2022). However, these two lakes have been under threat of hydrological drought in recent years. In particular, the construction and operation of the Three Gorges Reservoir (TGR) in 2003 changed the hydrological regime of the Yangtze River, and this change greatly influenced the hydrological connections and water balances between lakes and the Yangtze River and increased the seriousness of the drought problem

(Li *et al.* 2013; Yu *et al.* 2019). Frequent hydrological drought events have seriously affected local industrial and agricultural production, ecological security, and even threatened people's lives and health.

Numerous studies have analyzed and investigated hydrological drought in the Poyang Lake basin and the Dongting Lake basin (Sun *et al.* 2012; Liu *et al.* 2013; Zhang *et al.* 2014, 2016, 2019; Fan *et al.* 2017; Li *et al.* 2018; Yu *et al.* 2019; Ye *et al.* 2020). For example, Xue *et al.* (2014) analyzed the temporal and spatial characteristics of drought in the Dongting Lake basin based on the improved comprehensive drought index and wavelet theory and found that the autumn drought was the most serious at the seasonal scale. Huang *et al.* (2014) analyzed the detection, characteristics and challenges of hydrological drought at Dongting Lake in association with the TGR. Chen *et al.* (2013) identified the characteristic variables of hydrological drought based on run theory and analyzed the joint probability of the duration and intensity of hydrological drought in the Poyang Lake basin. Zhang *et al.* (2017) further constructed a hydrological drought index based on river runoff and lake water level and analyzed the joint probability of hydrological drought in Poyang Lake, the catchment and the Yangtze River using the copula function. In terms of the formation mechanism of hydrological drought in Poyang and Dongting Lakes, more scholars have focused on the TGR impact on the lake water level, water surface area, water resources and water exchange capacity with the Yangtze River (Li *et al.* 2013; Yu *et al.* 2019). For example, Yuan *et al.* (2014) used MODIS image data to extract the water surface area of Dongting Lake and found that the lake water area showed a shrinking trend following the operation of the TGR, and the impoundment behavior of the TGR in late summer and early autumn aggravated the continuous drought in Dongting Lake. Li *et al.* (2013) analyzed the evolution characteristics of water exchange capacity between Dongting Lake and the Yangtze River at different time scales. Their results showed that the spill division ability of the three outlets of the Yangtze River weakened after the operation of the TGR, and the amount of water entering the lake was reduced. Similarly, many scholars have also studied the impact of TGR on droughts in Poyang Lake. Zhang *et al.* (2014) investigated the role of the inflows from the Poyang Lake basin and the Yangtze River discharges on lake hydrology based on a hydrodynamic model. The hydrodynamic simulations showed that the changes in the hydrological regime of the Yangtze River caused by the TGR had a greater impact on seasonal drought in Poyang Lake, especially during autumn. Lai *et al.* (2014) established a hydrodynamic model for the middle reaches of the Yangtze River, and their simulations showed that the impact of the TGR on the Yangtze River discharge was highly spatially uneven. In autumn, impoundment accelerated the outflow from Poyang Lake and thus significantly decreased the lake water level. Other scholars have analyzed the impact of climate change and water cycle on hydrological drought in the middle reaches of the Yangtze River (Zhang *et al.* 2015; Li *et al.* 2020; Liu *et al.* 2020). The results showed that the decrease in precipitation and meteorological drought in the Dongting Lake basin were the main driving factors causing the decrease in runoff and the decline in lake water level at the annual scale (Cheng *et al.* 2016; Li *et al.* 2020). Similar results were found for the Poyang Lake basin (Liu *et al.* 2013; Ye *et al.* 2013; Zhang *et al.* 2014). Overall, these previous studies have promoted the understanding of hydrological drought in the middle reaches of the Yangtze River and the impact of the TGR.

However, due to the different distances from the ocean, the influences of atmospheric circulation on the Poyang and Dongting Lake basins and their spatial and temporal distributions of precipitation are varied. More importantly, Dongting Lake is approximately 300 km downstream from the TGR and 500 km upstream from Poyang Lake, and changes in the water regime caused by the TGR gradually attenuate from Yichang to Datong, resulting in very different strengths of river–lake interactions between the Yangtze River and Poyang and Dongting Lakes (Guo *et al.* 2012). Previous studies have focused little on comparing hydrological droughts in Poyang Lake and Dongting Lake and have not analyzed the differences in the impacts of the Yangtze River and the local catchment on hydrological drought events in Poyang and Dongting Lakes. This lack of research is not conducive to mitigating drought or providing early drought warnings in the middle reaches of the Yangtze River. Therefore, the objectives of the study are (1) to analyze the characteristics of hydrological drought in Poyang and Dongting Lakes during the period of 1964–2016, including the annual lowest water level, the average lake level in the dry season, the start date and duration of the dry season, and the intensity of hydrological drought events; (2) to investigate and compare the joint probability of concurrent hydrological drought in the lake–local catchment–Yangtze River system during different seasons based on the copula function and (3) to explore the relationship between the large-scale climate indices and hydrological drought in the two lakes. The results of this study can provide useful references and deep insights into hydrological droughts in the middle reaches of the Yangtze River.

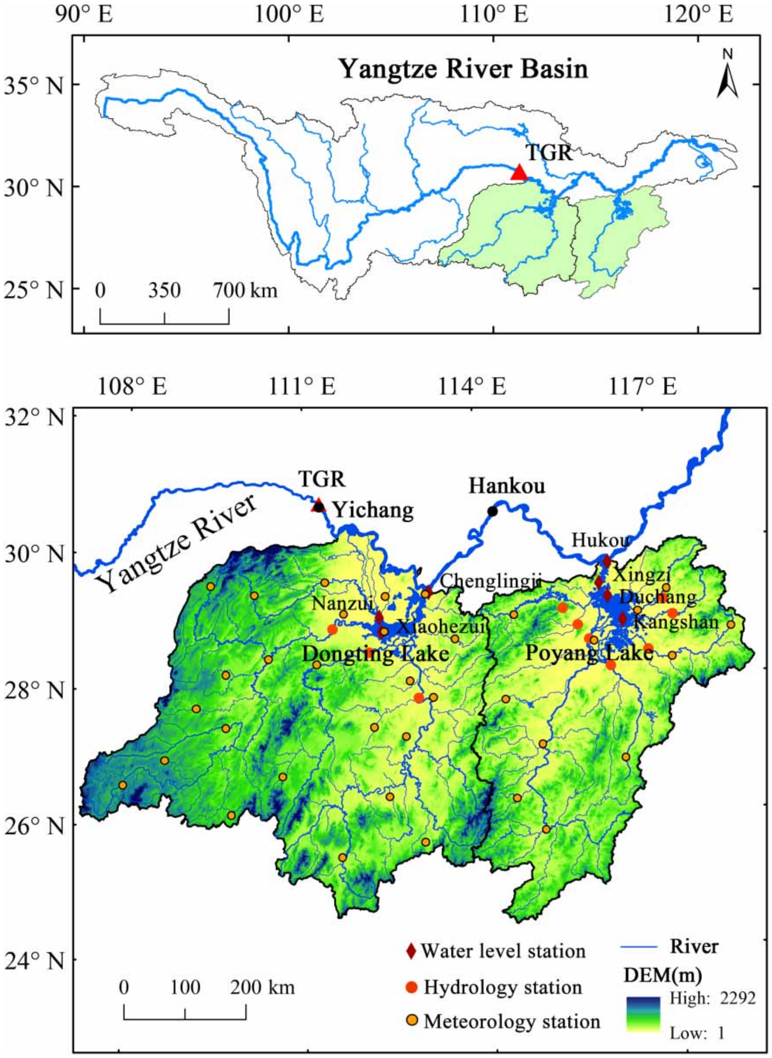


Figure 1 | Location of the study area and the distribution of hydrological and meteorological stations.

2. STUDY AREA AND DATA

2.1. Study area

Poyang and Dongting Lakes are located in the south bank of the middle reaches of the Yangtze River, China (Figure 1) and have maximum water areas of 3,163 and 2,500 km^2 in the flood season, respectively (Wu & Liu 2016). These two lakes are still naturally connected with the main stream of the Yangtze River. Poyang Lake receives water from five large rivers in its catchment and flows into the Yangtze River after being regulated by the lake. The drainage area of Poyang Lake is 16.2×10^4 km^2, and the average annual runoff is $1,451 \times 10^8$ m^3. Dongting Lake is formed by the confluence of the three distributary outlets of the Yangtze River (Songzi, Taiping and Ouchi) and four rivers in its catchment, and then it flows into the Yangtze River through a channel at Chenglingji. Dongting Lake consists of three sub-lakes, namely, west lake, south lake and east lake, with a total drainage area of approximately 26.2×10^4 km^2 and an average annual runoff of $1,645 \times 10^8$ m^3. The Poyang and Dongting Lake basins belong to a subtropical humid monsoon climate, with average air temperatures of 18.1 and 17.0 °C and average annual precipitations of 1,626 and 1,413 mm, respectively (Sun *et al.* 2012; Li *et al.* 2014, 2015, 2017a, 2017b). The precipitation in the two lake basins is concentrated, showing significant seasonal differences, so the seasonal distribution of runoff into each lake is also uneven. The water regime changes in the local basin and the Yangtze River directly affect the water level and areas of Poyang and Dongting Lakes (Zhang *et al.* 2022).

2.2. Data

The data used in this study mainly include hydrological data for Poyang Lake, Dongting Lake and their basins, as well as the discharges of the main stream of the middle reaches of the Yangtze River. The observed water level at Hukou, Xingzi, Duchang and Kangshan stations from 1964 to 2016 was selected to represent the water level changes of Poyang Lake, and the monthly runoff data from Waizhou, Lijiadu, Meigang, Hushan, Dufengkeng and Wanjiabu hydrological stations in the Poyang Lake basin were selected to reflect the water inflow into the lake. The water level records at Nanzui, Xiaohezui and Chenglingji stations during the same period were selected to describe the changes in the water level of Dongting Lake, and the runoff data at Taojiang, Taoyuan and Xiangtan hydrological stations in the Dongting Lake basin were used to reflect the changes in water inflow into Dongting Lake. The discharges of the Yangtze River at Yichang and Hankou stations were used to quantify hydrological drought in the main stream of the Yangtze River. These data were collected from the Hydrology Bureau of Changjiang Water Resources Commission, China, and the locations of these stations are shown in Figure 1. Moreover, these data have been widely used in various hydrological studies (Ye *et al.* 2013; Li *et al.* 2014, 2015, 2017a, 2017b) and their qualities have been tested and reliable. Additionally, regional climate indices, including the Southern Oscillation Index (SOI), the Arctic Oscillation (AO) index, the North Pacific Decadal Oscillation (PDO) and the El Niño 3.4 region index (NINO3.4), were collected from the National Centers for Environment Information (NCEI), National Oceanic and Atmospheric Administration (NOAA) of the United States (https://www.ncei.noaa.gov/access/monitoring/products) to analyze the causes of hydrological drought events.

3. METHODS

3.1. Nonstationary hydrological drought index

In this study, the time-varying standardized water level/runoff index (SWIt/SRIt) was used to identify the characteristics of hydrological drought and quantify the degree of drought. The definition of the SWIt/SRIt is similar to that of the standardized precipitation index (SPI), but it is based on nonstationary Gamma distribution (Sutanto *et al.* 2020). In order to consider the time-varying characteristics of the distribution parameters of the water level and runoff series in the changing environment, time-varying nonstationary Gamma models were established for the water level series of Poyang and Dongting Lakes, the runoff series of the two lake basins and the discharges of the Yangtze River at the seasonal scale (Sun *et al.* 2020). Finally, the cumulative distribution calculated by the optimal model was transformed into the normal distribution by the equal probability transformation method, and then the SWIt and SRIt were obtained (Rashid & Beecham 2019; Song *et al.* 2020). When the values of the SWIt and SRIt are greater than 0, there is no drought, and when they are less than 0, there is drought, and the smaller SWIt and SRIt values indicate greater drought intensity. This study mainly focuses on hydrological drought events with the SWIt/SRIt ≤ -1.

3.2. Copula function

Copula theory was first proposed by Sklar (1959) and has been widely used in the analysis of bivariate or multivariate probability distributions in hydrometeorological research. In this study, the Copula function was applied to quantify the joint probability of concurrent hydrological drought events in the lake–river system of the Poyang and Dongting Lake basins. Specifically, Gumbel, Clayton, Frank, Gaussion, *t* and Plackett Copula functions were used to fit the SWIt and SRIt series, and the relationship between the Kendall rank correlation coefficient τ and the parameter θ of the Copula function was established to estimate the parameters (Ravens 2000).

According to Copula theory, if two hydrological events X and Y have distributions $F_X(x)$ and $F_Y(y)$, respectively, their joint distribution $F(x, y)$ is obtained as follows (Sklar 1959):

$$F(x, y) = P(X \leq x, Y \leq y) = C_\theta(F_X(x), F_Y(y)) \tag{1}$$

where C is a Copula function representing the bivariate dependence structure of variables X and Y, and θ is an undetermined parameter. In this study, X and Y refer to the time series of SWIt and SRIt.

Kendall's rank correlation coefficient is calculated as follows (Genest & Favre 2007):

$$\tau = \frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}[(x_i - x_j)(y_i - y_j)] \tag{2}$$

where τ is Kendall's rank correlation coefficient, (x_i, x_j) are the SWIt and SRIt values in the corresponding period and n is the series length.

The joint return period for a hydrological drought event can be calculated as follows (Salvadori *et al.* 2011):

$$T(X \leq x, Y \leq y) = \frac{s}{C(F_X(x), F_Y(y))} \tag{3}$$

where s is the time interval of occurrence in the sequence. When the time scale of SWIt and SRIt is 3 months, $s = 0.25$ year.

3.3. Cross-wavelet analysis

Cross-wavelet analysis is an extension of the wavelet analysis method, which is used to analyze the correlation between two time series $[x(t), y(t)]$ in the time and frequency domains. In this study, in order to identify the key factors affecting hydrological drought at different times, cross-wavelet analysis of the hydrological drought index and the large-scale climate index was carried out to depict their phase structure and detailed characteristics in the time and frequency domains. The cross-wavelet energy spectrum can show the same energy spectrum region of $x(t)$ and $y(t)$ after wavelet transformation, which reflects the structural characteristics of the two series after wavelet transformation in the time–frequency domain. The advantage of the cross-wavelet energy spectrum is that the main oscillation period of the signal can be observed, and the evolution of the oscillation period with time at different time scales can also be more clearly observed.

Adopting the Morlet wavelet, the cross-wavelet spectrum between $x(t)$ and $y(t)$ is obtained as follows:

$$W_{xy}(a, \tau) = C_x(a, \tau)C'_y(a, \tau) \tag{4}$$

where C_x (a, τ) is the wavelet transform coefficient of $x(t)$, and C'_y (a, τ) is the complex conjugate of the wavelet transform coefficients of $y(t)$.

4. RESULTS

4.1. Variation of hydrological drought in the two lakes

The variations in the annual lowest lake level and the average lake level from October to December in Poyang and Dongting Lakes during the period of 1964–2016 are shown in Figure 2. The annual lowest lake level ranged from 6.07 m in 1979 to 8.72 m in 2016 in Poyang Lake, and from 17.42 m in 1972 to 20.67 m in 2016 in Dongting Lake. Both lakes showed a long-term upwards trend during the study period. However, the average lake level from October to December showed a significant downwards trend in both Poyang and Dongting Lakes, especially after 2003, and the average water level of the two lakes was significantly lower than that before 2003.

Additionally, the start date and duration of the dry season in the two lakes were compared and analyzed, as shown in Figure 2. The water level of Poyang Lake is lower than 12.0 m at the Hukou station and the water level of Dongting Lake is lower than 24.5 m at the Chenglingji station, indicating that they have entered the dry season. The start date of the dry season was depicted by the Julian day number, which is a continuous count of days from the first day of the year. Figure 2(b) and 2(d) shows that the Julian day numbers presented long-term decreasing trends, which means that the two lakes began their dry season earlier. Especially, Poyang and Dongting Lakes began to exhibit low water in October (Julian day <300) in the past 10 years, which was obviously earlier than the average times historically. At the same time, the dry season has become longer, even the duration has exceeded 200 days in the recent year.

Figure 3 shows the SWIt changes in Poyang and Dongting Lakes at the annual and seasonal scales. The change process of the SWIt in the two lakes is consistent; that is, the occurrence of hydrological drought in Poyang and Dongting Lakes was nearly synchronous at the annual scale. At the seasonal scale, the SWIt of the two lakes showed different trends during different seasons. In spring, the hydrological drought in the two lakes showed a further aggravating trend overall, and it was more significant in Poyang Lake. In autumn, both SWIt showed a significant downwards trend, indicating that the hydrological drought events in the two lakes were more serious, especially the intensity of hydrological drought in the two lakes increased year by year after 2003. Notably, in winter, the hydrological drought in Dongting Lake tended to be alleviated overall, and its frequency gradually decreased, while the hydrological drought in Poyang Lake still occurred frequently.

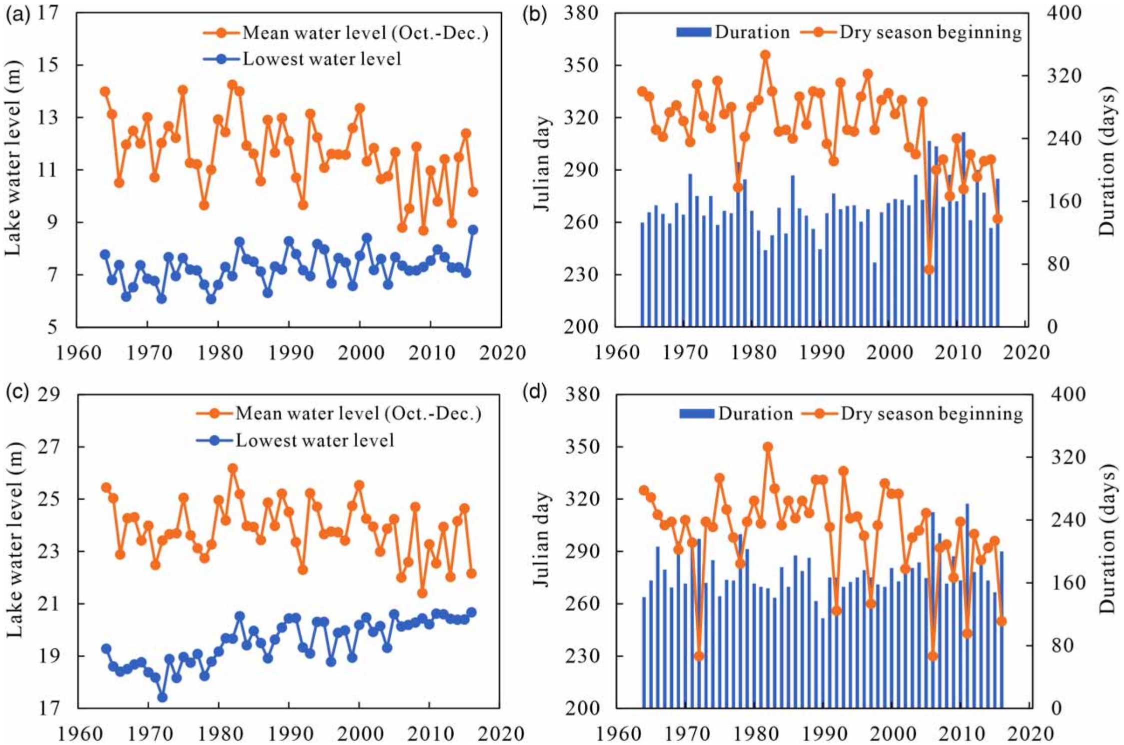


Figure 2 | Variation in the annual lowest lake level, average lake level, and the start date and duration of the dry season for Poyang Lake (a, b) and Dongting Lake (c, d).

According to the SWIt values, the hydrological droughts were divided into different grades. A SWIt value of less than −1.0 is considered to be a moderate drought, a value of less than −1.5 is defined as a severe drought, and a value of less than −2.0 is classified as an extreme drought. Figure 4 shows the frequency of hydrological drought events with different intensities in Poyang and Dongting Lakes in different decades and seasons. Hydrological drought events in Poyang and Dongting Lakes occurred most frequently in the 1970s. Two severe droughts and two moderate droughts occurred in Poyang Lake, and two severe droughts and one moderate drought occurred in Dongting Lake. Although the frequency of hydrological drought events in the two lakes was lower in the 2000 and 2010s, the intensity of drought was strong, and extreme drought events occurred in both lakes, indicating that the drought events in Poyang and Dongting Lakes became more serious after 2000. From the distribution of hydrological drought events in different seasons (Figure 4(b)), hydrological droughts in both lakes were the most serious in autumn. There were 12 and 15 hydrological drought events in Poyang Lake and Dongting Lake, respectively; moreover, most of the extreme hydrological drought events occurred in autumn.

4.2. Probability distribution of hydrological drought in two lakes

Based on the optimal marginal distribution function, the probability distribution characteristics of hydrological drought during different seasons in Poyang and Dongting Lakes are shown in Figure 5. The occurrence probabilities of hydrological drought in spring at Poyang and Dongting Lakes were 16.40 and 15.58%, respectively. During the study period, there were seven hydrological drought events that occurred in Poyang Lake, four of which occurred after 2003, while there were 11 hydrological drought events that occurred in Dongting Lake, 2 of which occurred after 2003. Although the number of hydrological drought events in Poyang Lake was less than that in Dongting Lake overall, the frequency of drought events in Poyang Lake after 2003 was greater, and the proportion was larger, which indicated that the spring hydrological drought in Poyang Lake was more serious than that in Dongting Lake in recent years. In autumn, the occurrence probabilities of hydrological drought in Poyang and Dongting Lakes were as high as 27.65 and 32.46%, and the recurrence periods were 0.90 and 0.77 years, respectively. During the study period, 12 hydrological drought events were identified in Poyang Lake, half of which occurred after 2003, while 15 hydrological drought events were identified in Dongting Lake, 7 of which occurred after

2003. In winter, the probability of hydrological drought in Poyang Lake was 14.26%, and five of the eight hydrological drought events occurred in 2003–2016, indicating that the winter hydrological drought in Poyang Lake had an aggravating trend after 2003. However, the probability of hydrological drought in Dongting Lake in winter was small (only 4.60%). Overall, the hydrological drought was aggravated in both Poyang and Dongting Lakes during autumn after 2003, and the drought in Dongting Lake was more serious than that in Poyang Lake. While, during spring and winter, the hydrological drought in Poyang Lake was more serious than that in Dongting Lake.

Figure 6 shows the joint probability of concurrent hydrological drought in the Poyang Lake–catchment–Yangtze River system at the seasonal scale. The joint probabilities of concurrent hydrological drought between Poyang Lake and its catchment in spring, summer, autumn and winter were 10.84, 7.23, 6.28 and 8.51%, respectively, while the values were 9.01, 10.56, 26.39 and 0.38% between Poyang Lake and the Yangtze River, respectively. The probability of concurrent hydrological

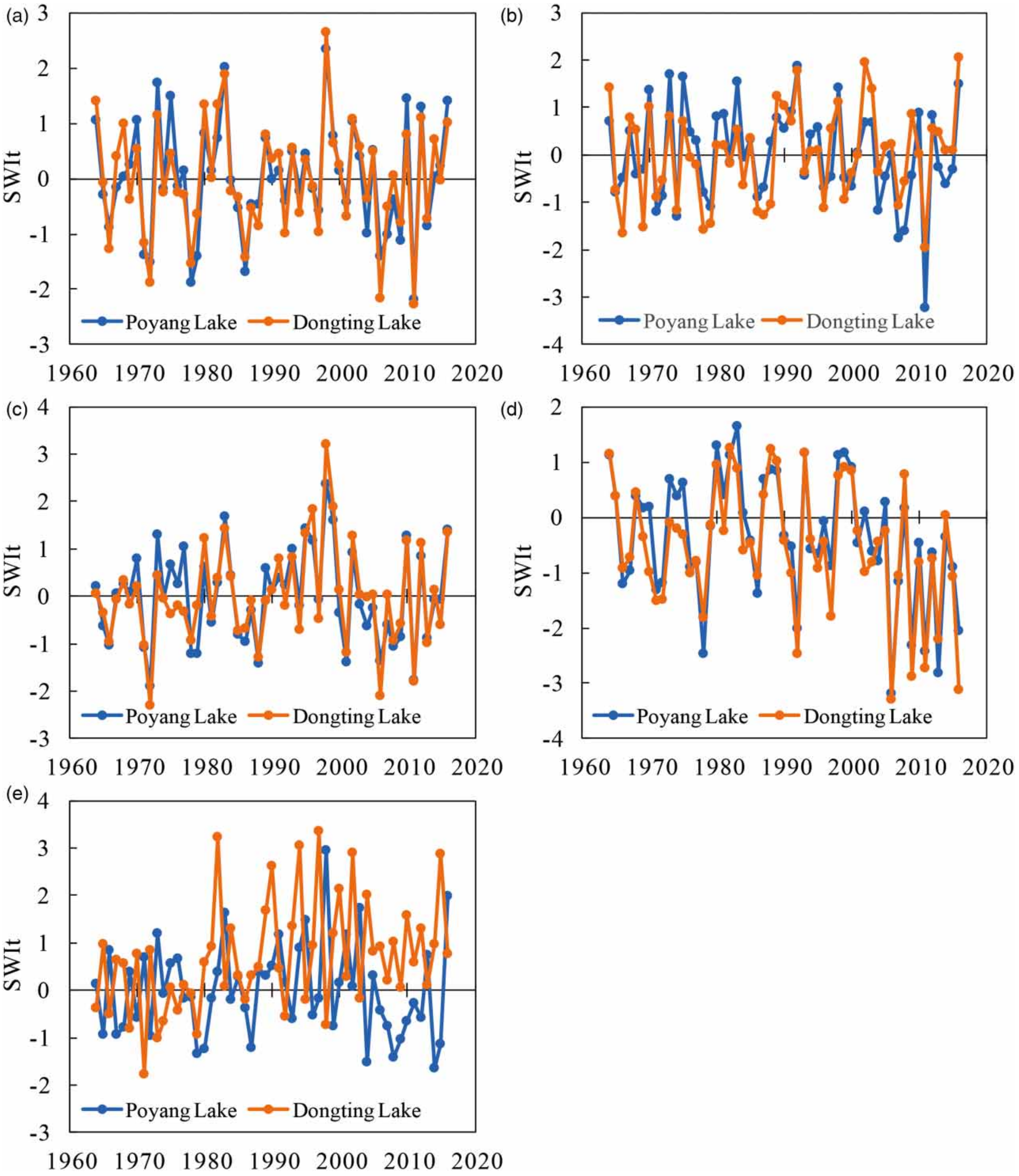


Figure 3 | Changes in the SWIt of Poyang and Dongting Lakes at annual (a) and seasonal scales (b: spring; c: summer; d: autumn; e: winter).

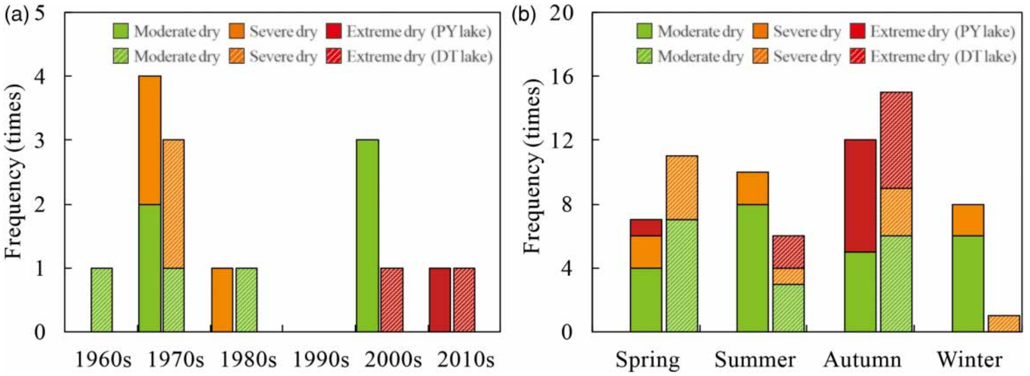


Figure 4 | Frequency of hydrological drought events with different intensities in different decades (a) and seasons (b).

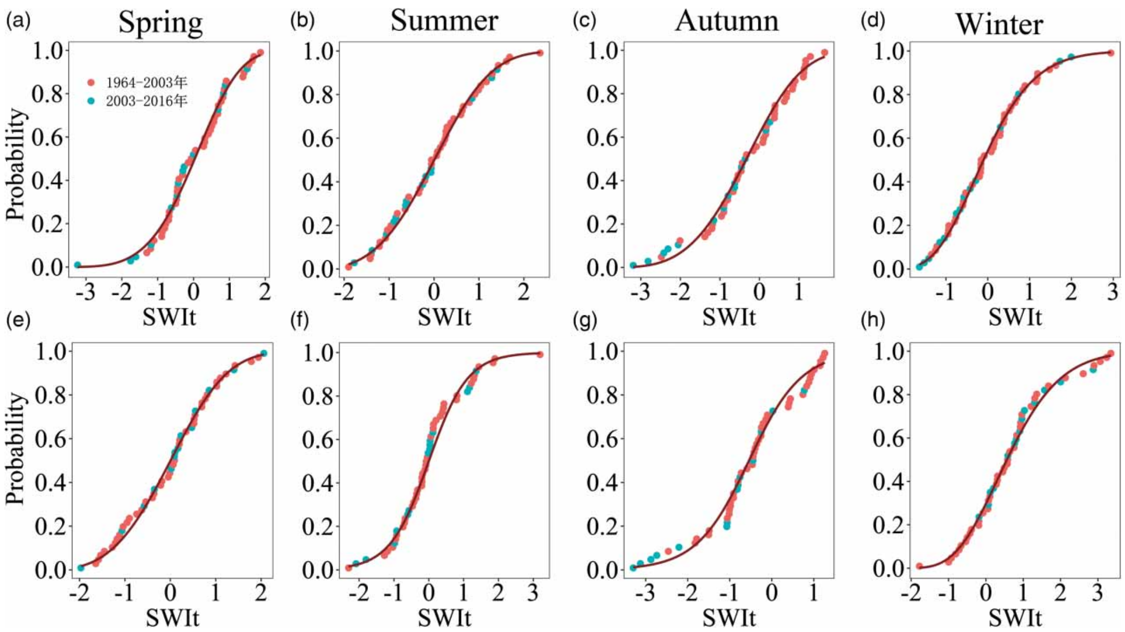


Figure 5 | Probability distribution of the SWIt for Poyang Lake (a–d) and Dongting Lake (e–h) at the seasonal scale.

drought in Poyang Lake and its catchment in spring was higher than that in other seasons. During 1964–2016, there were six concurrent hydrological drought events, four of which occurred during the period of 2003–2016, which indicated that the hydrological drought in Poyang Lake was significantly associated with the hydrological drought in its catchment after 2003, and the change in runoff from the basin played a leading role in the water level of Poyang Lake in spring. However, in autumn, the joint probability of Poyang Lake–Yangtze River concurrent hydrological drought was as high as 26.39%, and 10 hydrological drought events were identified during the study period, 5 of which occurred in 2003–2016, indicating that the hydrological droughts in Poyang Lake after 2003 were more consistent with the hydrological droughts in the main stream of the Yangtze River in autumn.

Figure 7 shows the joint probability of concurrent hydrological drought in the Dongting Lake–catchment–Yangtze River system at the seasonal scale. The joint probabilities of concurrent hydrological drought between Dongting Lake and its catchment in spring, summer, autumn and winter were 9.52, 7.64, 7.85 and 3.37%, respectively, while the values were 7.60, 8.20, 27.76 and 3.60% between Dongting Lake and the Yangtze River, respectively. The probability of concurrent hydrological drought in Dongting Lake and its catchment was higher in spring than that in other seasons. During 1964–2016, there

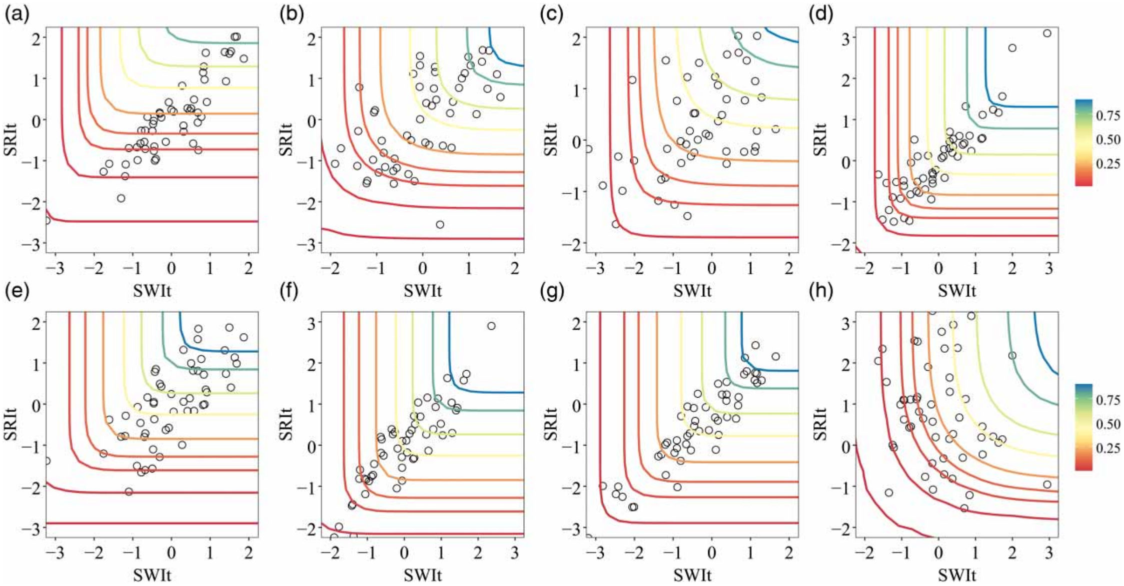


Figure 6 | Seasonal joint probability of concurrent droughts between Poyang Lake and its catchment (a–d) and between Poyang Lake and the Yangtze River (e–h).

were seven concurrent hydrological drought events, two of which occurred during the period of 2003–2016. For the concurrent hydrological drought between Dongting Lake and the Yangtze River, the joint probability was as high as 27.76% in autumn, and 13 concurrent hydrological drought events were identified during the study period, 7 of which occurred in 2003–2016, indicating that the hydrological droughts in Dongting Lake after 2003 were significantly associated with the hydrological drought in the main stream of the Yangtze River in autumn.

4.3. Correlation between hydrological drought and large-scale climate index

Mounting evidence has shown that there is a strong correlation between large-scale climate indices and extreme hydrological events (Aryal *et al.* 2018; Shen *et al.* 2022), and research on the correlation between climate change and hydrological drought

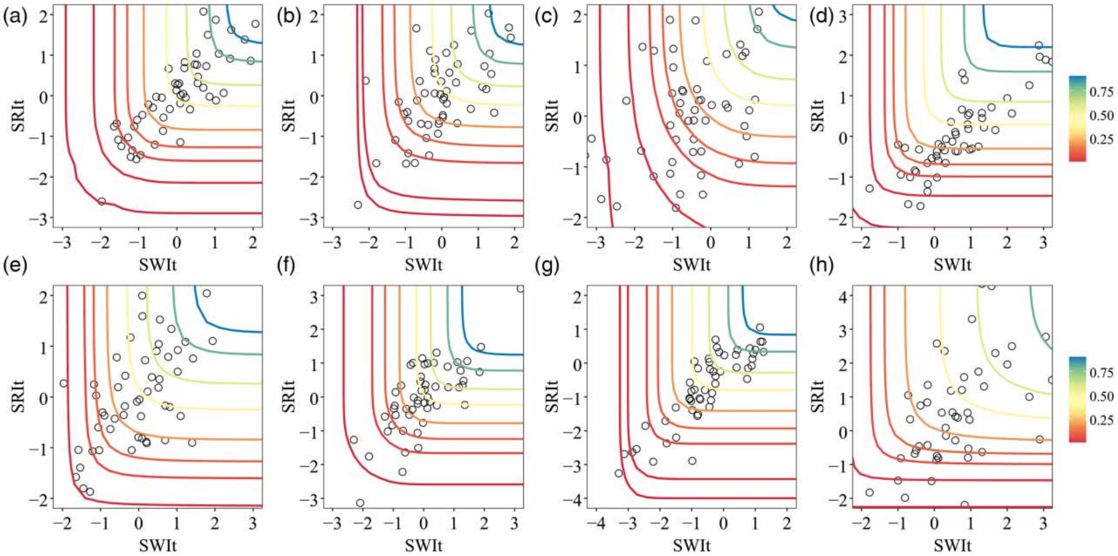


Figure 7 | Seasonal joint probability of concurrent droughts between Dongting Lake and its catchment (a–d) and between Dongting Lake and the Yangtze River (e–h).

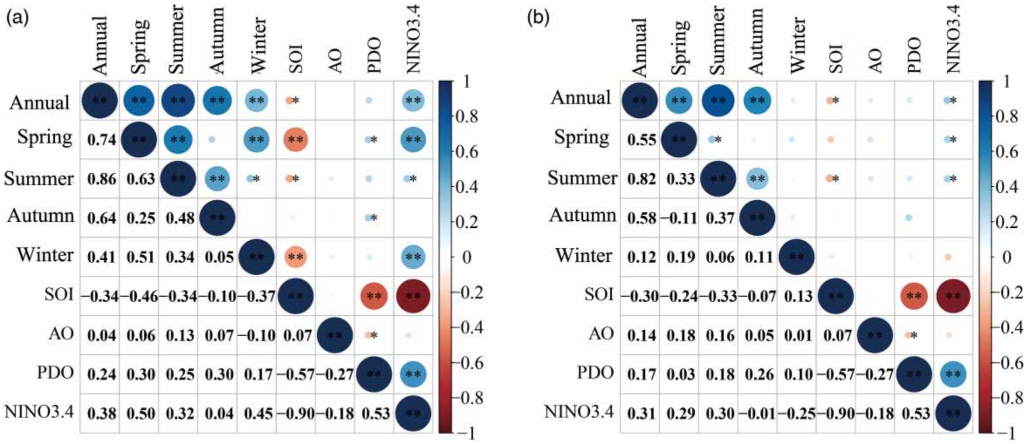


Figure 8 | Correlation between the SWIt and climate indices in Poyang Lake (a) and Dongting Lake (b).

events will help to reveal the formation mechanism of hydrological drought in lakes and their catchments. The time–lag correlation analysis between the SWIt of different time scales for Poyang and Dongting Lakes and the selected climate indices (SOI, AO, PDO and NINO3.4) was carried out with a 6-month lag, and the results are shown in Figure 8. The SWIt values for Poyang and Dongting Lakes were generally consistent with each climate index, but the impact of the climate index on both lakes was different at different time scales. At the annual scale, the hydrological drought indices of Poyang and Dongting Lakes were negatively correlated with the SOI, with correlation coefficients of −0.34 and −0.30, respectively, but they were positively correlated with NINO3.4, with correlation coefficients of 0.38 and 0.31, respectively. At the seasonal scale, the hydrological drought index of Poyang Lake in spring was negatively correlated with the SOI and positively correlated with the NINO3.4, with correlation coefficients of −0.46 and 0.50, respectively. The results indicated that the Southern Oscillation may alleviate and the El Niño phenomenon may aggravate spring hydrological drought in Poyang Lake. However, the correlation between the hydrological drought index and the climate index in Dongting Lake in spring was weak, and only NINO3.4 passed the 95% significance level, showing a positive correlation with a correlation coefficient of 0.29. In summer, the hydrological drought index of Poyang and Dongting Lakes was negatively correlated with the SOI (−0.34 and −0.33) and positively correlated with the NINO3.4 (0.32 and 0.30). Notably, the teleconnection relationship between the hydrological drought index in Poyang Lake and the climate index in autumn and winter was quite different from that in Dongting Lake. There was a significant positive correlation with the PDO (0.30) in autumn and a negative correlation with the SOI (−0.37) in winter in Poyang Lake, while there was no significant correlation between the hydrological drought index of Dongting Lake and the four selected climate indices in autumn and winter.

To further explore the driving relationship between each climate index and the hydrological drought index in both lakes, the wavelet power spectrum of different climate indices was created by cross-wavelet transformation. Figure 9 shows the cross-wavelet transformations between the SWIt of Poyang Lake and the four climate indices. The SWIt of Poyang Lake and the SOI had a positive correlation with a 7–8-year cycle during the period of 1978–1988 and a significant positive correlation with a 2–3-year cycle during the period of 2006–2011. There were significant negative correlations between the SWIt and NINO3.4 with 1–4-year and 2–3-year cycles during the period of 1970–1972 and 2006–2011, respectively. Moreover, the significant negative correlations were found between the SWIt and PDO with 1–2-year and 5-year cycles during the period of 1973–1976 and 1995–1997, respectively. For the AO, there was a positive correlation with an 8–9-year cycle during the period of 1980–1988, while there was a significant negative correlation with a 1–3-year cycle during the period of 2007–2013.

Figure 10 shows the cross-wavelet transformations between the SWIt of Dongting Lake and the four climate indices. The cross-wavelet power spectrum of the SWIt and the climate index for Dongting Lake was similar to those for Poyang Lake, but there were also some differences. The SWIt of Dongting Lake and the SOI had a positive correlation with an 8–10-year cycle during the period of 1980–1990 and a significant positive correlation with a 1–2-year cycle during the period of 2006–2011. Similarly, significant negative correlations were found between the SWIt of Dongting Lake and NINO3.4 with 3-year and 2–3-year cycles during the period of 1970–1972 and 2006–2010, respectively. Moreover, there was a negative correlation

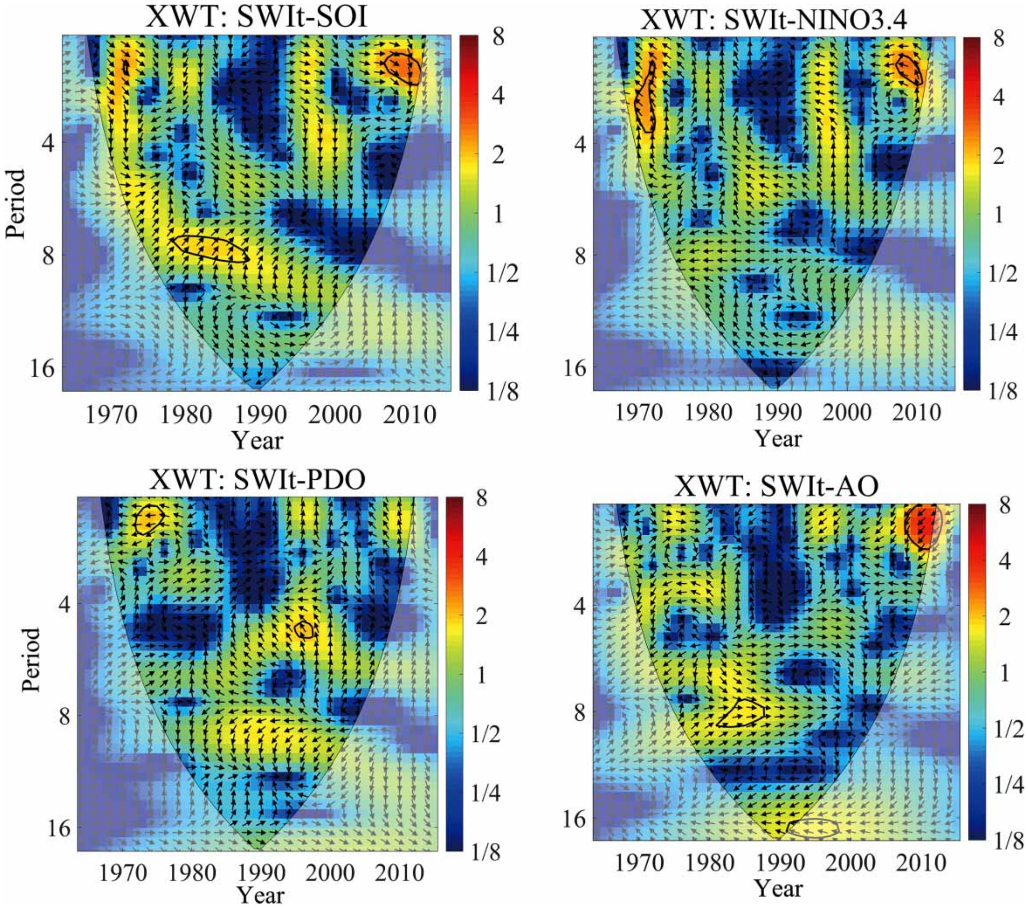


Figure 9 | The cross-wavelet transformations between the SWIt of Poyang Lake and the four climate indices.

between the SWIt and PDO with a 4–6-year cycle during the period of 1992–2002. For the AO, there was a positive correlation with an 8–10-year cycle during the period of 1985–1990, while there was a significant negative correlation with a 1–2-year cycle during the period of 2006–2011.

5. DISCUSSIONS

The hydrological drought of Poyang and Dongting Lake is affected by both the inflows of the local catchments and discharges of the Yangtze River, but the dominant factors change with time (Yuan *et al.* 2016). This study revealed that the joint probability of concurrent hydrological drought between Dongting Lake and its catchment was higher than that between Dongting Lake and the Yangtze River in spring, which indicated that the hydrological drought of Dongting Lake in spring was synchronous with the hydrological drought in the local catchment. The decrease in water inflow from the local catchment was the main factor driving hydrological drought in Dongting Lake in spring. This result was consistent with the study of Sun *et al.* (2015), and they believed that the spring drought in Dongting Lake was basically caused by the lack of water inflow from the local catchment. He *et al.* (2021) also revealed that the water volume of Dongting Lake was mainly affected by the inflow of the local catchment. While, in autumn, this study found that the hydrological drought of Dongting Lake was mainly affected by the discharge of the Yangtze River, with the high joint probability of simultaneous hydrological drought in the Dongting Lake–Yangtze River system (15.38%). Previous studies have shown that after the operation of the TGR, the water level–discharge relationship of the Yangtze River changed, and the impoundment of the reservoir during autumn significantly reduced the water level and discharge of the middle and lower reaches of the Yangtze River (Gao *et al.* 2013), which weakened the jacking effect of the Yangtze River on the two lakes and aggravated the low water phenomenon in the lakes (Ou *et al.* 2012; Guo *et al.* 2018). Lai *et al.* (2014) also found that the impoundment of the TGR in autumn caused the water level of Dongting

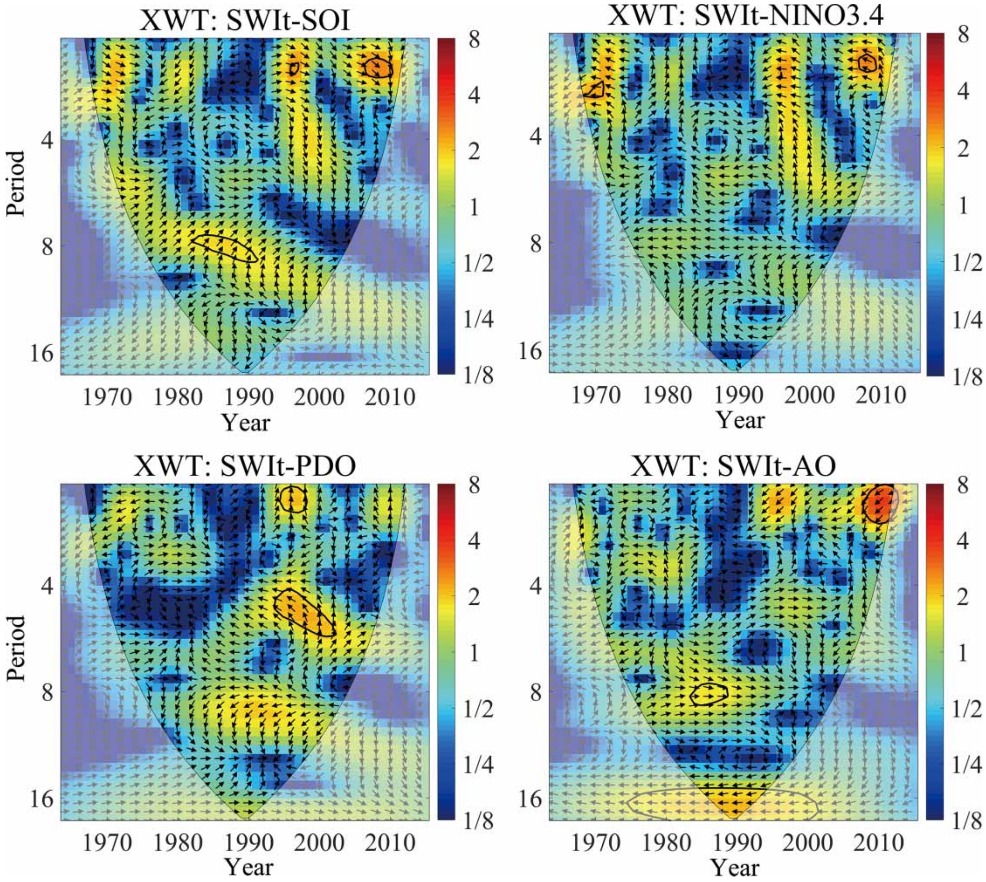


Figure 10 | The cross-wavelet transformations between the SWIt of Dongting Lake and the four climate indices.

Lake to drop rapidly and the low water level to appear ahead of schedule. On the other hand, the reduction of precipitation in the Dongting Lake basin also plays an important role. For example, the study of Ou *et al.* (2012) showed that the extreme drought event in Dongting Lake in autumn 2006 was caused by the sharp decrease in discharge of the Yangtze River and water inflow from the four rivers in the basin, with an average decrease by 74.7 and 30.4%, respectively.

A similar situation exists also in Poyang Lake. Fang *et al.* (2012) found that the operation of the TGR made the dry season of Poyang Lake start approximately 1 month ahead of schedule. Zhang *et al.* (2012) found that the average water level of Poyang Lake dropped by 2.0 m at the Hukou station and the jacking effect of the Yangtze River weakened after impoundment of the TGR, which increased the possibility of hydrological drought in Poyang Lake in summer and autumn.

In addition, the effects of other human activities on the hydrological drought of the two lakes cannot be ignored. According to the Statistic Bulletin on China Water Activities, there were 10,798 reservoirs with a total storage capacity of 32.8 billion m^3 in Jiangxi Province, including 30 large reservoirs (storage capacity $>$ 100 million m^3) and 251 medium reservoirs (storage capacity $>$ 10 million m^3), and 14,098 reservoirs with a total storage capacity of 51.4 billion m^3 in Hunan Province, including 45 large reservoirs and 359 medium reservoirs. The operation of these reservoirs directly changed the seasonal distribution of runoff of the five rivers in the Poyang Lake basin and the four rivers in the Dongting Lake basin. Additionally, with the prohibition of sand mining in the main stream of the Yangtze River in 2000, many sand dredgers entered Poyang Lake and Dongting Lake to conduct sand mining. Continuous sand mining has caused erosion of the lake basin, resulting in an increase in the gradient of the channel into the Yangtze River in the lake area (Yao *et al.* 2018), which accelerated lake water drainage to the Yangtze River and further aggravated the hydrological drought in the lake area (Yao *et al.* 2019). In addition, forestation in the two lake basins began in the 1980s, with the forest coverage of the Poyang and Dongting Lake basins increasing from 41 and 36.7% in 1989 to 61.2 and 59.6% in 2016, respectively (Ye *et al.* 2013; Yu *et al.* 2018). The increase in forest coverage led to an increase in regional evapotranspiration and interception, which undoubtedly resulted in a significant decrease in runoff on a monthly or seasonal scale. Moreover, the two lake plains are important grain bases in China, with large agricultural water consumption. For example, the agricultural water consumption in the Dongting Lake plain was 10.12 billion m^3 in 2016, accounting for more than 70% of the total water consumption. In particular, mid-September is the peak period of irrigation water for late rice and other crops, and a large number of agricultural irrigation water demand further aggravated the water shortage problem in Dongting Lake in autumn (Liang *et al.* 2021).

Overall, the impact process and mechanism of human activities on the hydrology and water resources of Poyang and Dongting Lakes are complex. In the context of the changing relationships of Yangtze River–Lake, it is necessary to strengthen the ecological environment construction and optimize the scheduling scheme of water conservancy projects to meet the demand of production and domestic and ecological water use (Yang *et al.* 2016). On the other hand, water-saving agriculture should be developed to improve the efficiency of water use in agricultural production. Quantitative assessment of the impact of different human activities on drought in Poyang and Dongting Lakes is the focus of the next step and further studies need to be conducted with quantitative hydrological and hydrodynamic simulations.

6. CONCLUSIONS

This study analyzed and compared the characteristics and differences in hydrological drought in Poyang and Dongting Lakes during the period of 1964–2016 and further investigated the correlation between hydrological drought and large-scale climate indices. The results of the study showed that the hydrological drought of Poyang and Dongting Lakes has become increasingly serious and their average lake level in the dry season decreased. The two lakes entered the dry season earlier; furthermore, the duration of the dry season was prolonged and the intensity of hydrological drought events increased. The occurrence probabilities of hydrological drought at Poyang and Dongting Lakes were 16.40 and 15.58% in spring, 27.65 and 32.46% in autumn, and 14.26 and 4.60% in winter, respectively. The hydrological drought of Poyang Lake was more serious than that of Dongting Lake in spring and winter, while, in autumn, it was not as serious as that of Dongting Lake. The joint probabilities of concurrent hydrological drought in the Lake–catchment systems were the highest in spring (10.84 and 9.52%) and the joint probabilities in the Lake–Yangtze River systems were the largest in autumn (26.39 and 27.76%). Finally, the changes in large-scale climate indices had an important effect on the hydrological drought of Poyang and Dongting Lakes. The SWIt of both lakes was negatively correlated with the SOI (−0.34 and −0.30) and positively correlated with NINO3.4 (0.38 and 0.31) at the annual scale. At the seasonal scale, the hydrological drought in Poyang Lake was more closely related to the changes in climate indices, while their correlation relationships were weak for Dongting Lake, especially in autumn and winter. In addition, the impoundment of the TGR and other human activities, such as sand mining, reservoir construction, agricultural production and forestation in the local catchment, played important roles in aggravating the hydrological drought that occurred in the two lakes.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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