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Spatio-Temporal Characteristics of Standardized Precipitation Index in the Taihu Basin during 1951-2000

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Abstract: Spatial and temporal characteristics of standardized precipitation index (SPI), which is widely used for drought/flood monitoring, are investigated in this study. The purpose is to obtain a reasonable primary scheme of zoning on the basis of drought/ wetness conditions in the study area. Spatio-temporal distributions of SPI with the time scales of 3 months and 12 months are investigated with the datasets of precipitation in the Taihu basin during past decades (1951-2000). Results indicate that SPI series of 3 months show random fluctuation while that of 12 months behaves like 1/*f* noise. SPI series of 3 months show little trend while that of 12 months show significant trend at several stations. Drought magnitude (DM) is also estimated on the basis of SPI values to assess drought condition. No trend is detected in DMs with time scales of both 3 months and 12 months. Spatial variability of DM is analyzed by mapping the DM with 12 months for extreme drought and wetness, and regional characteristics are analyzed for DM.

Key words: spatio-temporal distribution; Taihu basin; standardized precipitation index; time scale; zoning

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0 Introduction

Drought is a recurrent natural hazard that usually results from the reduction of precipitation and lasts an extended period of time, e.g., several months, one year or more[1-3]. The American Meteorological Society[4] had suggested four types of drought: meteorological, agricultural, hydrological and socioeconomic ones. There is no universal definition of drought to date because of the various impacts on both natural and social environment. Therefore, the impacts and their spatial and temporal variability cannot be assessed with a universal approach or criteria. Many drought indices were proposed for measuring and monitoring drought in practice[5], but most of them are limited in specified regions. The Standardized Precipitation Index proposed by Mckee *et al*[6], however, provides a versatile functional definition for drought. It is a useful tool for monitoring and predicting climatic or meteorological conditions. Neither streamflow nor soil moisture is coupled in the estimation of standardized precipitation index (SPI), because it may significantly increase the complexity of computation. However, alteration of hydrological regime also can be inferred to some extent because of the universal and significant relationship between precipitation and streamflow. Because of its simple computation and low data requirement (with only precipitation records) but with powerful capability of representation and prediction on climatic/meteorological condition, SPI has been widely used for drought monitoring as well as flood risk monitoring and assessment[7]. For example, Tsakiris *et al*[8] made an attempt to establish a drought watching system based on SPI. Hayes *et al*[9] examined the drought that occurred in America in 1996 using SPI and the results showed that SPI was an effective tool for drought monitoring. Seiler *et al*[10] used SPI to detect floods that occurred in Argentina in the past 25 years and SPI was proved to be an effective trigger of flood risk.

Drought is one of the most frequent natural disasters in the Taihu basin[11,12]. The Taihu basin plays an important role with the multifunction of flood control, irrigation, water supply, aquaculture, etc., in the local area. However, it is difficult, in such a large basin, to implement basin management with a scheme centered on the Taihu Lake. Region-based basin management may be a proper notion for the management of the Taihu basin which is trans-provincial or trans-regional. Huang *et al*[13] investigated the long-term trends in several climatic variables as well as their spatial distributions. In this paper, the drought/wetness conditions are investigated by examining the spatio-temporal characteristics of SPI in the Taihu basin.

1 Study Area Description

The Taihu basin, with an area of 36 895 km^2, is located in the middle and lower reaches of the Yangtze River and covers parts of three provinces (Jiangsu, Zhejiang and Anhui) and Shanghai City. The area of the lakes is more than 2 000 km^2 in the basin. Flat-land covered with dense network of rivers counts for about 67% of the total area in the Taihu basin and the remainder of which is hilly or mountainous area. Average annual precipitation ranges from 1 010 mm to 1 400 mm in the basin, and most precipitation occurs between June and August in the year. Data of precipitation collected from nine meteorological stations within or around the Taihu basin (Fig. 1), provided by the China Meteorological Data Sharing Service System[14], is used in this study. The period of available data at each station is shown in Table 1.

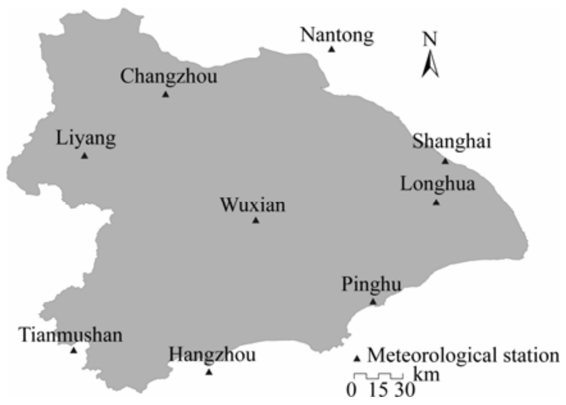

Fig. 1 The meteorological stations within or around the Taihu basin

Table 1 Starting and ending years of data at each station

Station	Starting year	Ending year	Length of time/a
Changzhou	1952	2000	49
Hangzhou	1951	2000	50
Liyang	1953	2000	48
Longhua	1951	1998	48
Nantong	1951	2000	50
Pinghu	1954	2000	47
Shanghai	1951	2000	50
Tianmushan	1956	1998	43
Wuxian	1956	2000	45

2 Method Description

2.1 Standardized Precipitation Index

The standardized precipitation index (SPI) was proposed by McKee *et al*[6] for drought monitoring in Colorado and the details are listed in Table 2. Standardized precipitation is simply the difference between precipitation and the mean and divided by the standard deviation where the mean and standard deviation are determined from a specified period of past records. SPI is an index based on the probability distribution of precipitation time series with a long-term record. The cumulative distribution is transformed to a normal distribution with a mean of zero and standard deviation of one since the probability distribution is determined by fitting an incomplete gamma distribution to the data. SPI values are computed for time scales of both 3 months and 12 months which are related with the meteorological and hydrological drought, respectively.

Table 2 Drought / wetness categories defined by SPI values

SPI value	Drought/Wetness category	Code
⩾ 2.0	extreme wetness	4
[1.5, 2.0)	severe wetness	3
[1.0, 1.5)	moderate wetness	2
(0.0, 1.0)	mild wetness	1
0	normal	0
(−1.0, 0)	mild drought	−1
(1.5, −1.0]	moderate drought	−2
(−2.0, −1.5]	severe drought	−3
⩽−2.0	extreme drought	−4

modified from Ref. [6]

2.2 Drought Magnitude

SPI values indicate the onset and ending of drought /wetness events and current drought intensity as well.

However, duration of drought is usually more valuable for investigating or assessing the drought conditions in the past. Thus, drought magnitude (DM) defined as a measure of the accumulated magnitude of drought is proposed[6]:

$$\mathrm{DM}=\sum_{j=1}^{m}\mathrm{SPI}_{ij} \quad (1)$$

where j denotes the j-th month of a drought and m is the ending of the drought for the i time scale. Apparently, DM can be used to represent the wetness conditions when SPI values greater than zero are accumulated. DM is signed herein so that the negative values of DM account for drought magnitude while the positive values of DM are computed for measuring wetness magnitude. Many drought/wetness events have a DM being very similar to the duration in months because most of the SPI values are between −2.0 and 2.0[6]. Average drought magnitude, dividing total DM by the count of drought events, can be computed to estimate average drought intensity for each drought category so as to compare each other over periods of records with different lengths.

2.3 Scaling Exponent

Scaling exponent α can reveal the autocorrelation structure, which provides useful information about the inherent "memory", in a time series[15]. If α = 0.5, there is no correlation and series is uncorrelated (white noise); if $a > 0.5$, the series is correlated, i.e., with long-range memory; if $a < 0.5$, the series is anticorrelated. Scaling exponents of SPI series are estimated to explore its randomness and autocorrelation by using detrended fluctuation analysis (DFA) method (see Ref. [16] for more details). DFA is a scaling analysis method, which is robust for most nonstationary time series, widely used to estimate long-range power-law correlations in signals[17].

3 Result Analysis

3.1 SPI Values

SPI values for scales of 3 months and 12 months are estimated and shown in Fig. 2. Almost all SPI values for both 3 months and 12 months fall in the range of [–4, 4], while most are between [−1, 1]. SPI values for 12 months often vary slower than that of 3 months, which fluctuates distinctly at short-term. That is, drought changes as the time scale changes. Drought with short time scale has high frequency and that with long time scale becomes less frequent with longer duration.

Scaling exponents for SPI series are computed using DFA method and are shown in Table 3. Scaling exponents of the SPI series with 3 months are all around 0.6, which indicates that these SPI series are little auto-correlated but with random fluctuations. Scaling

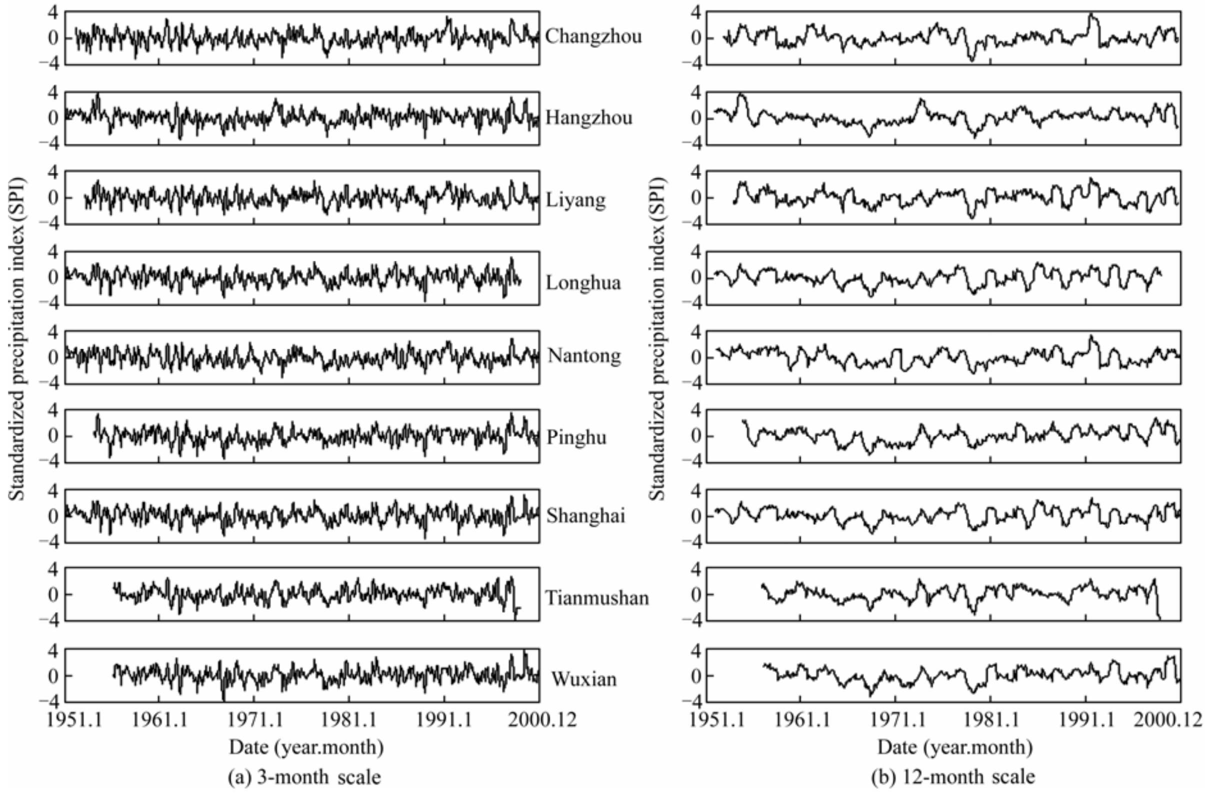

Fig. 2 SPI series of different time scales for the nine stations

Corresponding station names are placed in the center from top to bottom

Table 3 Scaling exponents α of SPI series

Station	3-month scale	12-month scale
Changzhou	0.61	1.06
Hangzhou	0.69	1.14
Liyang	0.62	1.03
Longhua	0.59	0.97
Nantong	0.64	1.04
Pinghu	0.62	0.99
Shanghai	0.61	1.00
Tianmushan	0.66	1.06
Wuxian	0.61	1.04

exponents of the SPI series with 12 months are around 1.0 indicating that these SPI series behave like $1/f$ noise, which occurs in many natural systems. There is little variation among stations for scaling exponents of SPI series for both 3 months and 12 months.

Trends in SPI series are also investigated using the statistics of Mann-Kendall test[18] at 95% of confidence level. SPI series of 3 months at Pinghu station shows an upward trend while that of other stations shows no trend. SPI series at Hangzhou, Pinghu and Wuxian stations show an upward trend and that of Nantong station shows a downward trend, while no trend is detected for other stations for time scale of 12 month.

3.2 Drought Magnitude

Drought magnitude (DM) is computed for time scales of 3 months and 12 months, respectively, and shown in Fig. 3. Drought with long time scale (12 months) has long drought duration thereby high drought magnitude. DM with the time scale of 3 months show frequent shift changes between positive and negative values, while transforms between the states of drought and wetness is undertaking more slowly for the time scale of 12 months. No trend is detected in drought magnitude for both time scales of 3 months and 12 months using Mann-Kendall test.

Average drought magnitudes (ADM), dividing total drought magnitude by the number of drought events, for each drought category are estimated to compare the drought magnitude between stations with different periods of precipitation records. ADMs for the time scales of 3 months and 12 months are listed in Table 4 and Table 5, respectively. The drought categories are denoted by integer numbers (see Table 2 for details) in these tables. ADMs with time scale of 3 months are smaller than that of 12 months in general since drought duration increases and drought frequency reduces when time scale increases as mentioned above. The averages of ADMs for all drought categories are listed in the last row in these tables. There is little variation of ADMs for 3 months among stations for each drought category, while that for 12 months is larger, especially for extreme drought (denoted by −4) and extreme wetness (denoted by 4).

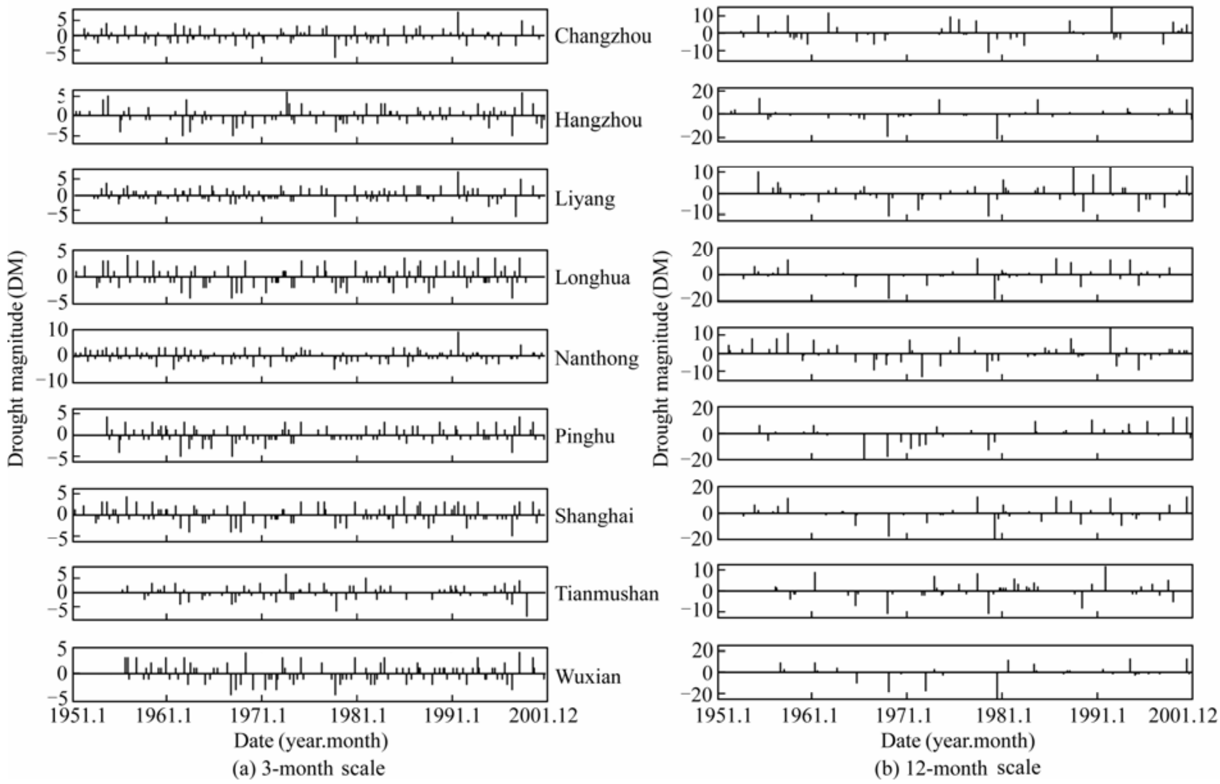

Fig. 3 Drought magnitude (DM) with different time scales for the nine stations

Corresponding station names are placed in the center from top to bottom

Table 4 ADMs for each drought category with time scale of 3 months

Station	Drought category							
	–4	–3	–2	–1	1	2	3	4
Changzhou	1.15	1.28	1.28	1.90	1.92	1.20	1.32	2.29
Hangzhou	1.89	1.24	1.30	1.86	2.16	1.26	1.09	2.13
Liyang	1.00	1.32	1.32	1.95	1.75	1.26	1.33	1.43
Longhua	1.60	1.19	1.17	1.74	1.99	1.24	1.18	1.80
Nantong	1.10	1.26	1.47	1.76	2.04	1.37	1.39	1.75
Pinghu	1.67	1.11	1.02	1.89	1.90	1.25	1.44	2.17
Shanghai	1.60	1.11	1.20	1.87	1.99	1.35	1.30	1.67
Tianmushan	1.17	1.65	1.25	2.14	1.87	1.20	1.24	1.33
Wuxian	1.27	1.28	1.16	1.90	1.79	1.24	1.12	1.50
Average value	1.38	1.27	1.24	1.89	1.93	1.26	1.27	1.79

Note: The integers in the header row denote the drought categories that listed in Table 2

Table 5 ADMs for each drought category with time scale of 12 months

Station	Drought category							
	–4	–3	–2	–1	1	2	3	4
Changzhou	5.00	1.14	2.13	3.90	3.57	2.50	2.56	6.50
Hangzhou	4.25	1.78	1.96	3.87	3.89	1.84	2.00	6.00
Liyang	3.25	1.54	1.69	3.24	3.87	2.28	2.18	1.83
Longhua	2.50	1.61	1.74	3.81	3.49	2.34	1.86	1.67
Nantong	2.40	1.56	2.10	3.65	3.73	2.35	1.91	7.00
Pinghu	4.50	1.95	2.16	3.59	4.16	2.43	1.88	2.00
Shanghai	2.14	1.75	1.90	3.79	3.67	2.67	2.31	1.75
Tianmushan	4.00	1.89	1.65	3.68	3.34	2.46	1.13	1.67
Wuxian	2.75	2.06	1.68	3.69	3.65	2.21	1.82	6.00
Average value	3.42	1.70	1.89	3.69	3.71	2.34	1.96	3.82

Note: The integers in the header row denote the drought categories that listed in Table 2

Spatial distribution of ADMs with the time scale of 12 months is exhibited by mapping their isolines for extreme drought (Fig. 4(a)) and extreme wetness (Fig. 4(b)), in which the ADMs show large variation among stations. Large values of ADMs for extreme droughts occur in the southwest (Hangzhou and Tianmushan stations) and northwest (Changzhou and Liyang stations) of the Taihu basin, while those of extreme wetness occur in the south (Hangzhou station), north (Nantong and Changzhou stations) and the center (Wuxian station) of the Taihu basin. Southeast of the Taihu basin (Longhua and Shanghai stations) has small ADMs for both extreme drought and extreme wetness with the time scale of 12 months.

The relationship between drought/wetness events and El Niño is initially investigated by estimating the cross correlation of the southern oscillation index (SOI) and drought magnitude. The SOI is calculated from the monthly fluctuations in the air pressure difference between Tahiti and Darwin[19]. Data of SOI may be obtained from the website of Bureau of Meteorology, Australia[20]. Sustained negative values of SOI usually indicate El Niño events accompanied by sustained warming while positive values of SOI indicate La Niña phenomenon. Therefore,

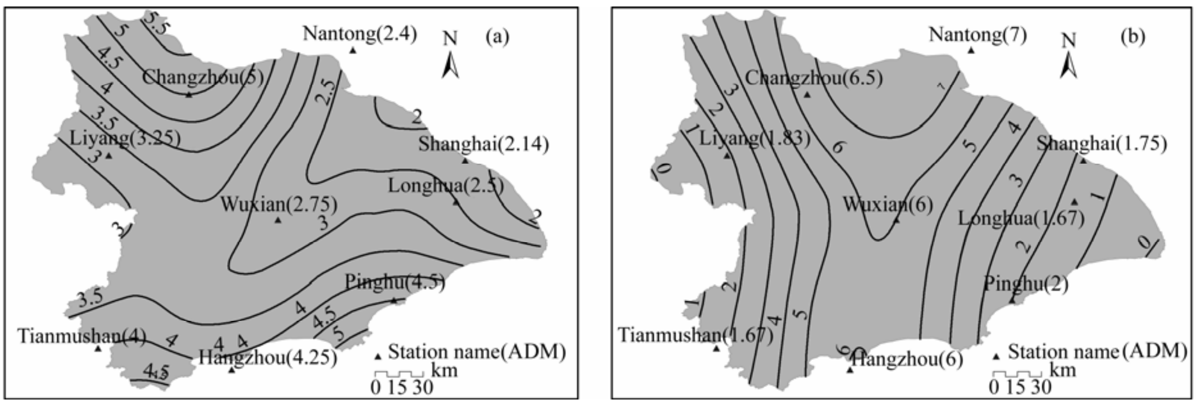

Fig. 4 ADM and isoline for extreme drought (a) and extreme wetness (b) with the time scale of 12 month

significant correlations between the SOI and drought magnitude imply that drought (wetness) events may be significantly influenced by El Niño or La Niña. Figure 5 shows the cross correlations between the SOI and drought magnitude with time scales of 3 months and 12 months for nine stations. Negative correlations, being statistically significant with a lag of 2 months, are found at five stations (Hangzhou, Longhua, Pinghu, Shanghai and Tianmushan) at the short time scale (3 months). There are also significant positive correlations with a lag of about one year (11-12 months) at Changzhou, Nantong, Pinghu and Shanghai stations. Six stations (Changzhou, Liyang, Longhua, Nantong, Shanghai, Tianmushan) show significant correlations with a lag of one year (11-13 months) between SOI and drought magnitude and one station (Hangzhou) shows negative correlation at the time scale of 12 months. El Niño affects the droughts with 3 months at short-term (2 months) and those with 12 months over a period of one year. The periods of 2 months and a year can be considered as effective periods of influence of El Niño on precipitation or drought. It seems that DM with 3 months occurring in the south and southeast of the Taihu basin and DM with 12 months occurring in the northwest and southeast of the Taihu basin are significantly affected by El Niño phenomenon.

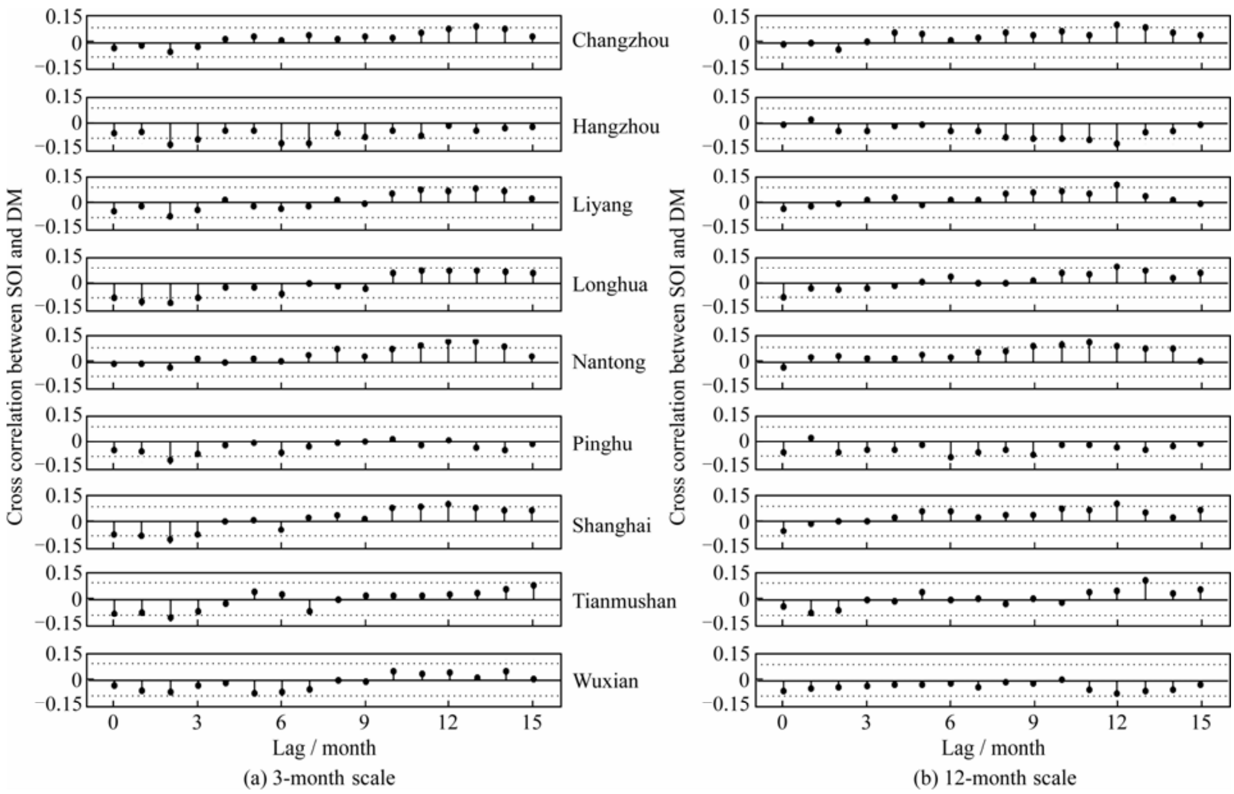

Fig. 5 Cross correlation between SOI and drought magnitude with different time scales for the nine stations

Note: Corresponding station names are placed in the center from top to bottom, dash lines in the graphs denote the upper and lower confidence levels of 95%

4 Conclusion

Standardized precipitation index (SPI) is proposed to assess the drought/wetness condition in the Taihu basin in this study. Monthly precipitation data from nine stations in the Taihu basin are used for SPI estimation. Results show that drought with time scale of 12 months has longer duration and lower frequency than that with time scale of 3 months. Scaling exponents (α) are estimated for SPI series of 3 months and 12 months, respectively, and show little variation among stations. SPI series of 3 months exhibit near random fluctuations and that of 12 month behaves like $1/f$ noise. It seems that the former has low predictability. Only one station (Pinghu) shows upward trend for SPI series of 3 months and three stations (Hangzhou, Pinghu and Wuxian) show upward trend and one station (Nantong) shows downward trend for SPI series of 12 months.

Drought magnitude (DM) is estimated to examine the drought duration for each drought event in past decades. Results show that DM with longer time scale has higher value than that with shorter time scale. No trend is detected in DM with time scales of both 3 months and 12 months at nine stations. Average DMs (ADMs) with 12 months show large variation among stations in the events of extreme drought and wetness. Map of spatial distribution of ADMs with 12 months for extreme drought and wetness indicates that the southeast, south and north of the Taihu basin show spatial heterogeneity in precipitation and drought condition. Cross correlation between SOI and DM series shows that drought condition in the Taihu basin may be significantly influenced by El Niño/La Niña.

SPI is a suitable index for the assessment and monitoring of droughts. The inherent standard normal distribution of SPI values facilitates further investigation with statistical analysis for temporal characteristics. It is also a proper approach to explore spatial variability of precipitation or drought phenomenon since it is a geographically transferrable index rather than a region-based one. Though both temporal trend and spatial variability are investigated in this study, further investigation is still needed, especially for spatial variability, due to the low resolution of available data from a sparse network of gauging stations. Nevertheless, the work presented in this study is useful for preparing a primary zoning scheme in the Taihu basin which will be further investigated in the ongoing study in the future.

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