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Multiscale hydro-meteorological factors variations and its links to large-scale atmospheric circulation systems in the source region of Yangtze River

Jian Tang*, Hui-Qun Cao

Basin Water Environmental Research Department, Changjiang River Scientific Research Institute, Wuhan, Hubei, China

Key Lab of Basin Water Resource and Eco-environmental Science in Hubei Province, Changjiang River Scientific Research Institute, Wuhan, Hubei, China

* Correspondence author

Dr. Jian Tang

Changjiang River Scientific Research Institute

No. 23 Huangpu Street, Wuhan, Hubei, China, 430010

E-mail: tang0815@yeah.net Tel: +86 27 82820873. Fax: +86 27 82820873

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Abstract: Studying hydro-meteorological factors variations and its links to large-scale atmospheric circulation systems can facilitate the understanding of the hydrological processes and sustainable water resources management in the source region of the Yangtze River (SRYR). Currently, researches mostly focused on the temporal and spatial variation characteristics in hydro-meteorological factors; however, researches on the hydro-meteorological variations and its links to large-scale atmospheric circulation systems in the SRYR are scarce. Based on long-term hydro-meteorological and reanalysis data, this research investigated multiscale variations of hydro-meteorological factors and its links to large-scale atmospheric circulation characteristic indices during 1957~2012 in the SRYR. The results showed that the amounts of streamflows and precipitation in the SRYR declined during the 1990s. Since the 2000s, the amounts of streamflows and precipitation had increased significantly climate in the SRYR. The change trends of precipitation and streamflows in the SRYR are synergetic at annual and seasonal scales, and have three significant periods, namely 3~5 years, 15-20 years and 30-40 years. The South Asia monsoon (SAM) plays a relatively more important role in the hydro-meteorological factors changes in the SRYR. The relative contributions of SAM to streamflows and precipitation changes were 83.6% and 78%, respectively. During the driest (wettest) year, the SAM is relatively weak (strong), and brings less (more) southwest airflow into the SRYR, less (more) precipitation and streamflows will be generated in the SRYR.

Key words: hydro-meteorological factors, Large-scale atmospheric circulation systems, South Asia monsoon, streamflows, source region of the Yangtze River

1. Introduction

Hydro-meteorological factors are greatly influenced by large-scale atmospheric circulation systems that vary on multiple time scales. In recent decades, researchers have been paying increasing attentions to the linkages between large-scale atmospheric circulation systems and hydro-meteorological factors in river basins [1, 2]. Such research could facilitate explanation and understanding of the water cycle and hydrological processes [3, 4]. These research topics are therefore essential for sustainable water resource management and protection [5, 6].

The source region of the Yangtze River (SRYR), is located in the hinterland of Qinghai-Tibet Plateau, plays an important role in regulating the hydrological processes in the Yangtze River basin of China, and even in the Southeast Asia [7, 8]. Therefore, the hydro-meteorological factors variations and its links to influencing factors in the SRYR have attracted much attention [9-11]. Large-scale atmospheric circulation systems play an important role in affecting the hydro-meteorological in the SRYR [3, 12]. Research topics that clarify the linkages between hydro-meteorological factors variations and large-scale atmospheric circulation systems need to be addressed in the SRYR [3, 13].

Over the last few decades, the SRYR experienced evident climate changes, which have changed regional atmospheric hydrological cycles. Climate change and the induced hydro-meteorological variations in the SRYR directly affect the lives of people and animals that depend on the river. A large number of studies therefore have been carried out on the changes and correlations of hydro-meteorological factors in the SRYR. Based on long-term meteorological data, multiscale characteristics of temperature and precipitation were explored in the SRYR [14, 15]. Varieties of statistical methods were used to analyze the trend and periodic variations of hydro-meteorological factors in the SRYR [10, 16]. To improve the understanding of the effects of climate change on the streamflows, many efforts had been devoted to analyze the relationships between streamflows and meteorological factors in the SRYR. The glacier variations and its influences on streamflows are studied in the SRYR by using stable isotopes [17]. The hydrological interactions in the atmosphere-vegetation-soil system were explored by using available filed observations [18]. Correlation analysis and water balance model results were further used to identify the key factor influencing the streamflows in the SRYR [19, 20].

These researches improve the understanding of the temporal and spatial variation characteristics in hydro-meteorological factors, as well as the relationship between the streamflows and meteorological factors. However, research on the hydro-meteorological variations and its links to large-scale atmospheric circulation systems in the SRYR are scarce [3, 21]. The relationships between hydro-meteorological variations and large-scale atmospheric circulation systems in the SRYR are still poorly understood. Therefore, it is essential to explore the hydro-meteorological variations and its links to large-scale atmospheric circulation systems in the SRYR.

In view of the above, the aim of this study is to 1) analyze the multiscale characteristics of trend and periodicity for the hydro-meteorological factors in the SRYR; 2) identify and clarify the important large-scale atmospheric circulation factor in the SRYR; and 3) explore and qualify the multiscale relationships between the hydro-meteorological factors and the large-scale atmospheric circulation factor. Research results especially vital for the future sustainable water resources management decisions in the SRYR.

2. Study area

Located in the central region of Qinghai-Tibet Plateau, the SRYR has an area of 158,000 km^2, and accounts for 8.8% of the area of Yangtze River basin. The SRYR provides 20% of the water volume of the Yangtze River [16], and therefore plays an important role in regional hydrological processes. The SRYR is mainly composed of three source flows named Tuotuo River, Dangqu River and Chumaer River. Tuotuo River, the main source of Yangtze River, originates from Jianggendiru Glacier. Dangqu River and Chumaer River are the south and north branch, respectively. 545 km downstream from the confluence of the three source flows, Zhimenda hydrological station, which is the national-level station located at the outlets of the SRYR (Figure 1). Large-scale atmospheric systems including El Niño-Southern Oscillation (ENSO), the South Asia monsoon (SAM), and the East Asia monsoon (EAM), play roles in affecting the weather and climate in the SRYR [3]. The climate of the SRYR is considered having cold-dry feature, where the mean annual temperature is -1.7~5.5°C, mean annual precipitation 270~410 mm.

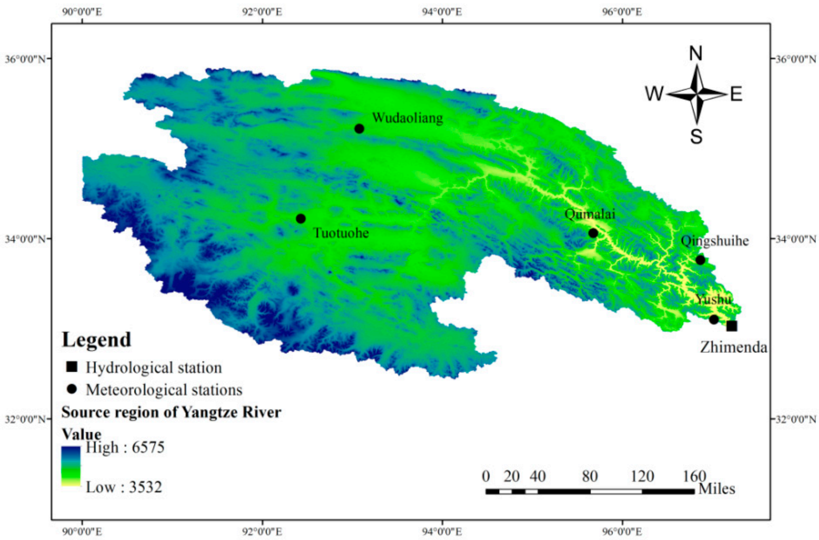

Figure 1. Sketch map of the SRYR.

3. Materials and methods

3.1. Data acquisition and processing

Monthly streamflows of Zhimenda hydrological station are used to in this study, and provided by the Hydrology Bureau of Qinghai Province. Due to the harsh natural environmental conditions, meteorological stations in the SRYR are scarce. Monthly meteorological data from the only five national meteorological stations (Tuotuo River, Wudaoliang, Qumalai, Qingshuihe and Yushu) are obtained from Chinese National Meteorological Centre. Streamflows and meteorological data are quality controlled, and have a continuous record from 1957 to 2012. The areal average monthly precipitation in the SRYR was calculated according to the Thiessen polygon method.

Three large-scale atmospheric circulation characteristic indices were employed in this study, including the Southern Oscillation Index (SOI), EAM and SAM. SOI is usually used to characterize the intensity of an ENSO event [22, 23]. SOI is a standardized index measure of large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific during El Niño and La Niña episodes. Therefore, SOI was employed to characterize the intensity of an ENSO event in this research. SOI were collected from http://www.cpc.ncep.noaa.gov/data/indices/soi. EAM indices were calculated from NCEP reanalysis data (850 hPa meridional wind averaged over 20~30°N and 110~130°E) by applying the formula defined by Li and Zeng (2005) [24]. SAM indices were calculated based on the formula defined by Goswami et al. (1999) (the differences in values between 850 hPa and 200 hPa zonal wind were averaged over 10~30°N, 70~110°E) [25]. All of the reanalysis data used in the calculation processes were collected from the following website: http://www.esrl.noaa.gov/psd/data/gridded /data.ncep.reanalysis.pressure.html.

3.2. Trend analysis for hydro-meteorological factors

The Mann-Kendall method has been widely used to assess trends in hydro-meteorological data [26]; hence it was adopted to explore trends in hydro-meteorological data of the SRYR.

The Mann-Kendall method calculates the Kendall rank correlation of a time series. The test statistic *S* of a time series is calculated using the following formula:

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sgn(x_j\text{-}x_k) \tag{1}$$

$$sgn(x_j\text{-}x_k)\begin{cases}1 \ \ if\ x_j>x_k\\ 0 \ \ if\ x_j=x_k\\ \text{-}1\ if\ x_j<x_k\end{cases} \tag{2}$$

where x_j and x_k are the streamflows values during periods *j* and *k* ($j > k$), respectively; and *n* is the length of the times series.

The values and variances of *S* (*S* and Var(*S*)) are used to calculate the test statistic *Z* as follows:

$$Z=\begin{cases}\dfrac{S\text{-}1}{\sqrt{Var(S)}} & if\ S>0\\ 0 & if\ \ S=0\\ \dfrac{S+1}{\sqrt{Var(S)}} & if\ \ S<0\end{cases} \tag{3}$$

The significance of a trend is tested by comparing the absolute value of *Z* with the standard normal variant at the desired significance level *α*. when the absolute value of Z is greater than $Z_{1-\alpha/2}$, the null hypothesis of an upward or a downward trend in the data can be rejected at significance level *α*. A positive *Z* value indicates an increasing trend; while, a negative *Z* value indicates a decreasing trend.

3.3. Wavelet analysis methods

Wavelet analysis methods are powerful method for analyzing variability modes within a time series [27, 28]. It has been widely applied in analyzing hydro-meteorological factors variations at multi-time scales [29]. Wavelet transform and wavelet coherence analysis

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methods are therefore selected and performed on hydro-meteorological time series of the SRYR.

Wavelet transform is the decomposition of target time series n by a mother wavelet:

$$W_n(s,t)=|s|^{-\frac{1}{2}}\int_{-\infty}^{\infty}n(t)\psi^{*}_{s,t}(t)\,dt \tag{4}$$

where $W_n(s,t)$ is wavelet coefficient, and denotes the wavelet transform of time series at scales s and times t. $\psi^{*}_{s,t}$ is derived through contraction and expansion of the mother wavelet. In this paper, the Morlet wavelet was used as the mother wavelet. The Morlet wavelet is defined as:

$$\psi(t)=\pi^{-\frac{1}{4}}e^{iw_0 t}e^{\frac{-t^2}{2}} \tag{5}$$

where w_0 is the non-dimensional frequency, and w_0 is set at 6 [30].

3.4. Water vapor fluxes calculation

Water vapor fluxes are one of the most important parts of hydrological processes, and certainly an important cause for regional hydro-meteorological factors changes [31]. The driving effects of large-scale atmospheric circulation systems on hydro-meteorological factors were further revealed by the analysis of water vapor fluxes in the SRYR. The water vapor fluxes were calculated based on the NCEP reanalysis data [32]. The formulas are listed as following:

$$Q=\frac{1}{g}\int_{p_u}^{p_s}qVdp=Q_\lambda i+Q_\varphi j$$

$$Q_\lambda=\frac{1}{g}\int_{p_u}^{p_s}qudp \tag{6}$$

$$Q_\varphi=\frac{1}{g}\int_{p_u}^{p_s}qvdp$$

where Q is the mean water vapor content of a column. g is the acceleration of gravity. p_s and p_v are the lower limit and upper limit air pressures, respectively. q is specific humidity. V is wind velocity vector. Q_λ and Q_φ are the zonal component and radial component of the vertically integrated total mean vapor fluxes, respectively. i and j refer to the unit vectors directed positively to the east and north, respectively. u and v are the zonal wind and radial wind, respectively.

4. Results

4.1. Multiscale hydro-meteorological factors variations in the SRYR

As shown in Figure 2, precipitation in the SRYR shows an increasing trend, but it is not statistically significant at the 0.05 level. Under the impact of climate warming, the monsoon and associated water vapor fluxes in the SRYR are affected, leading to the increase of precipitation. Even though the meteorological stations and the lengths of time series were different in researches, the views that held on precipitation increase in the SRYR in recent years were basically the same [33].

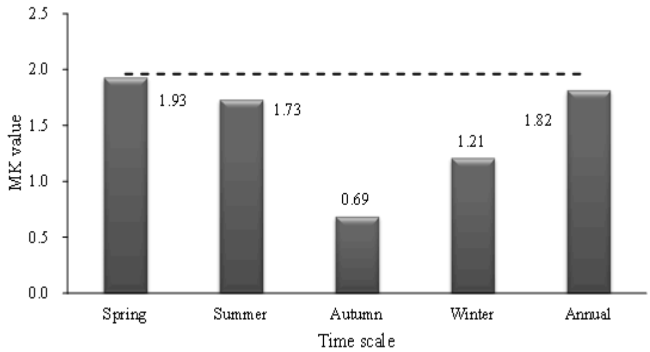

Figure 2. Trend analysis results of precipitation in the SRYR during 1957-2012. (The dotted line indicates it is statistically significant at the 0.05 level.)

Precipitation showed a decreasing trend in summer and autumn during the 1990s. Precipitation in most rivers source regions of Qinghai-Tibet Plateau showed a decreasing trend during the 1990s, which was especially obvious in the SRYR. After the 2000s, precipitation in the SRYR significantly increased (Table 1).

Table 1. Decadal changes of precipitation in the SRYR.

	Before 1960s (mm)	1970s (mm)	1980s (mm)	1990s (mm)	After 2000s (mm)
Spring	18.3	24.0	24.5	26.3	101.2
Summer	204.5	211.9	237.2	207.8	939.5
Autumn	165.3	165.5	172.4	149.0	719.9
Winter	7.5	7.9	9.1	10.7	33.9
Annual	98.9	102.3	110.8	98.5	448.6

Figure 3 illustrates the trend analysis results of streamflows in Zhimenda hydrological stations during 1957~2012. At annual and seasonal scales, streamflows in the SRYR shows an increasing trend, and the change trends in spring and winter are statistically significant at the 0.05 level. Glacial meltwater accounts for over 25% of streamflows in the main stream of the SRYR [34]. The rises of air temperature in winter and spring, prolong the glacier ablation period, and cause the increases in the ablation of the glaciers. The glacial meltwater further leads to the increase of streamflows in winter and spring.

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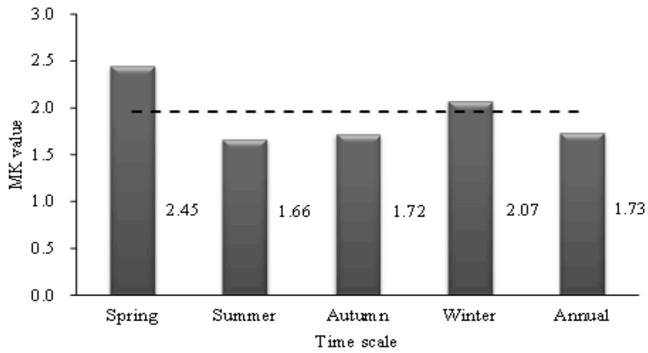


Figure 3. Trend analysis results of streamflows in Zhimenda hydrological station during 1957~2012. (The dotted line indicates it is statistically significant at the 0.05 level.)

Due to the decrease of precipitation in the SRYR during the 1990s, streamflows also showed a decreasing trend, and entered a relatively low-flow period. Similar to the change trend of precipitation, streamflows in the SRYR showed a significant increasing trend after the 2000s (Table 2).

Table 2. Decadal changes of streamflows in Zhimenda hydrological station.

	Before 1960s (m^3/s)	**1970s (m^3/s)**	**1980s (m^3/s)**	**1990s (m^3/s)**	**After 2000s (m^3/s)**
Spring	94.9	94.9	95.8	94.0	110.6
Summer	604.4	544.0	797.9	561.0	745.6
Autumn	732.4	715.4	797.0	626.4	956.2
Winter	102.4	99.8	113.9	96.0	129.1
Annual	383.5	363.5	451.1	344.3	485.4

Generally speaking, the change trends of precipitation and streamflows in the SRYR are synergetic at annual and seasonal scales. During 1957~2012, the overall trends in precipitation and streamflows were increasing, but the decadal changes had volatility. The climate in the SRYR was dry during the 1990s. Since the 2000s, precipitation had increased significantly, and the climate in the SRYR tended to become moist.

To better reveal the periodicities of hydro-meteorological factors in the SRYR, real part wavelet coefficient of streamflows and precipitation was calculated and shown in Figure 4. The annual average streamflows of Zhimenda hydrological station have three significant periods, namely 3~5 years, 15-20 years and 30-40 years (Figure 4a). Previous researches had confirmed that Yangtze River streamflows have significant periods of 3~4 years, 7~8 years and 10-40 years [35]. This periodic behavior of streamflows was considered to be caused by periodic changes in precipitation [36]. Real part wavelet coefficient contour map of precipitation in the SRYR confirms the opinion (Figure 4b). In terms of annual average precipitation in the SRYR, there were periodical change rules at three time scales, namely 3-5 years, 15-20 years and 30-40years.

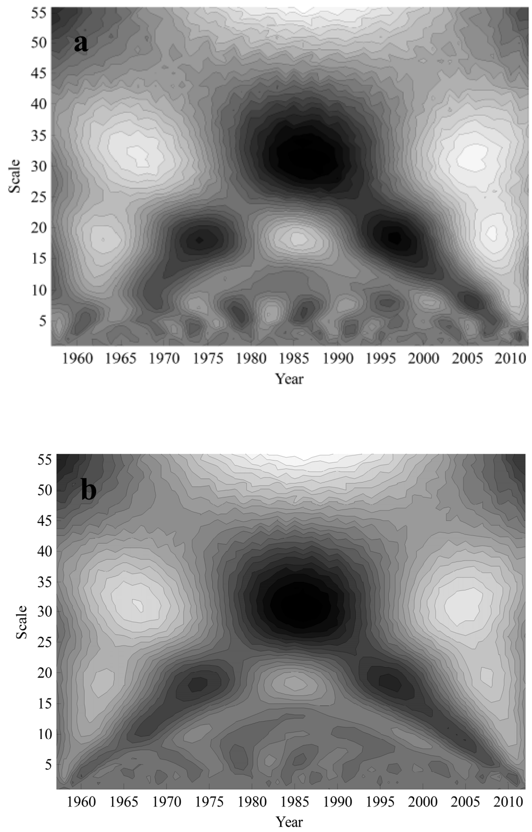


Figure 4. Real part wavelet coefficient contour map of annual average streamflows (a) and precipitation (b) in the SRYR.

4.2. Links between hydro-meteorological factors and large-scale atmospheric circulation systems in the SRYR

Previous researches demonstrated the linear correlation can be easy-operation and time-saving to explore the teleconnections between streamflows and large–scale atmospheric circulation systems [37]. Therefore, the linear correlation was adopted to identify the important atmospheric circulation factor in the SRYR.

As shown in Figure 5. Monthly SOI, EAM, and SAM indexes are positively correlated with monthly streamflows of Zhimenda hydrological station. The correlation coefficients of streamflows and large-scale atmospheric circulation characteristic indices rank as follows: SAM > EAM > SOI. The correlation coefficients of SOI, EAM and streamflows are 0 and 0.14, respectively. The correlation between the SAM and streamflows is good, and the correlation coefficient is 0.68.

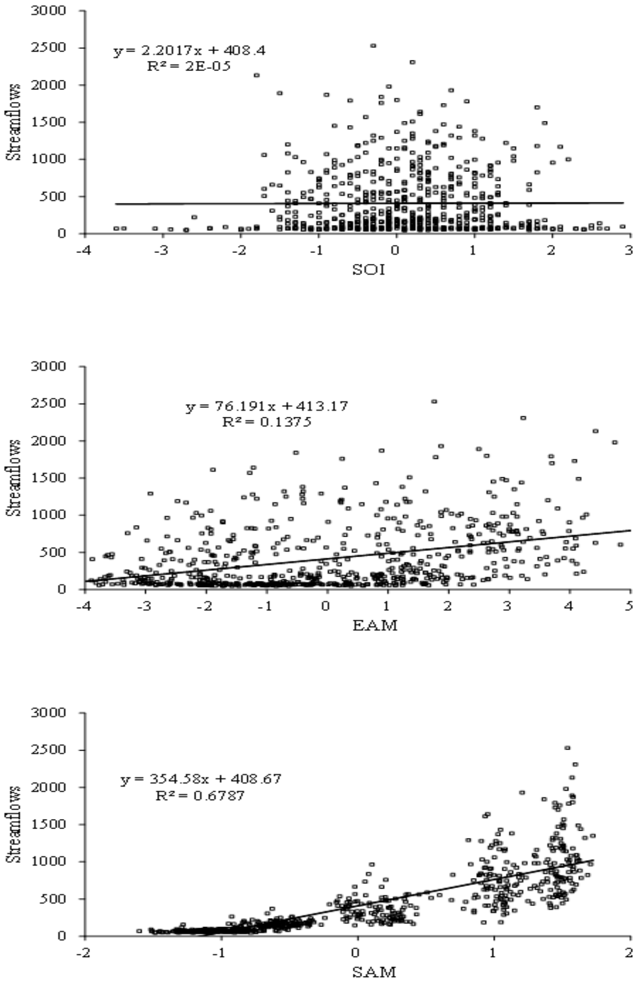
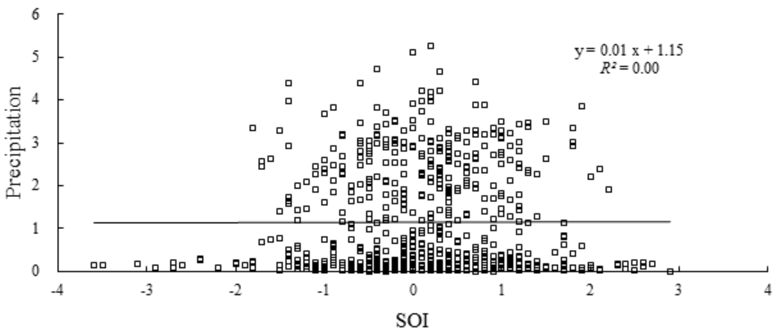


Figure 5. Linear correlations between streamflows and large-scale atmospheric circulation characteristic indices.

The correlations between monthly precipitation and large scale circulation factors in the SRYR are shown in Figure 6. SOI has a weak correlation with precipitation. The correlation coefficient is close to 0. EAM and SAM are positively correlated with precipitation, and the correlation coefficients are 0.35 and 0.82, respectively.



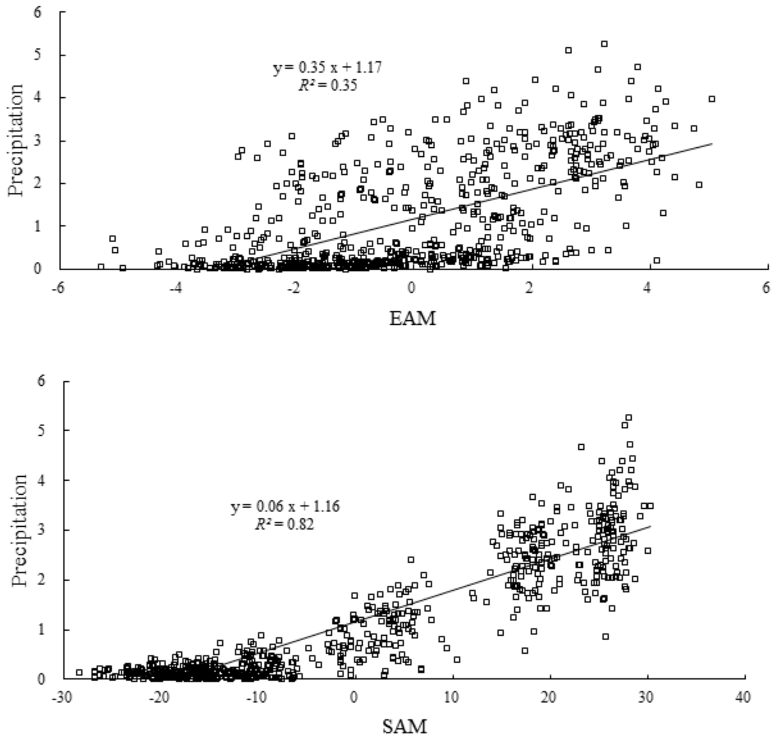


Figure 6. Linear relationships between precipitation and large-scale atmospheric circulation indices in the SRYR.

EAM and SAM have close relationships with streamflow and precipitation in the SRYR (Figures 5 and 6). Multiple linear regression analysis is used to analyze influences of the two monsoon indices (EAM and SAM) on the streamflows and precipitation, and to determine the contributions of the two monsoon indices to the streamflows and precipitation changes in the SRYR. As shown in Table 3. The contributions of SAM to streamflows and precipitation changes were 83.6% and 78%, respectively. The contributions rate of EAM to streamflows and precipitation changes were 16.4% and 22.0%。The SAM plays a relatively more important role in the streamflows and precipitation changes in the SRYR.

Table 3. Contributions of the EAM and SAM to the streamflows and precipitation changes in the SRYR.

Contribution	Monsoon	Streamflows	Precipitation
Standardized regression coefficient	EAM	0.10	0.18
	SAM	0.51	0.64
Contribution（%）	EAM	16.4	22.0
	SAM	83.6	78.0

The decadal changes of the EAM and SAM indices are further analyzed, and the decadal changes characteristics of the two monsoon indices are similar (Table 4). Before 1980s, the two monsoon indices showed a weak attenuation trend. After 90s, the two monsoon indices began to increase. There is a positive correlation between the two monsoons

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and streamflows and precipitation (Figures 5 and 6). The streamflows and precipitation therefore will increase with the two monsoons indices, and gradually show a wet change trend. The results further confirm the change trends of precipitation and streamflows in the SRYR (Tables 1 and 2). If the intensity of the two monsoon systems continues to increase, the climate will characteristic by wet in the SRYR.

Table 4. Decadal change trends of indices of EAM and SAM.

	1957~1969	1970~1979	1980~1989	1990~1999	2000~2012
MK value of the EAM	-1.18	-1.14	-0.67	0.04	0.45
MK value of the SAM	0.12	-0.33	0.59	0.51	0.55

The convergence of the water vapor transport is associated with the large–scale atmospheric circulation systems, and is an important condition for the formation and generation of precipitation and streamflows. The maximum water vapor transport center is located at the 850 hPa geopotential height in the SRYR [38]. Exploring the water vapor fluxes changes at the 850 hPa geopotential height, can therefore facilitate the understanding of the impacts of large–scale atmospheric circulation systems on hydro-meteorological factors in the SRYR.

Figure 7 illustrates the distributions of water vapor flux at 850 hPa geopotential height in typical hydrological years in the SRYR. As is shown, the vector arrows of the wind fields indicate a southwest airflow field in the SRYR. The SAM brings the southwest airflow into the SRYR, and forms the regional dominant airflow direction and water vapor source. Therefore, change of the SAM will be a key factor affecting the formation and generation of precipitation and streamflows in the SRYR. The water vapor fluxes in the SRYR are mainly located at the outlets of the SRYR. From the southwest to the northwest, the water vapor fluxes in the SRYR are gradually reducing. During the driest (wettest) year, the SAM is relatively weak (strong), and brings less (more) southwest airflow into the SRYR, less (more) precipitation and streamflows will be generated in the SRYR.

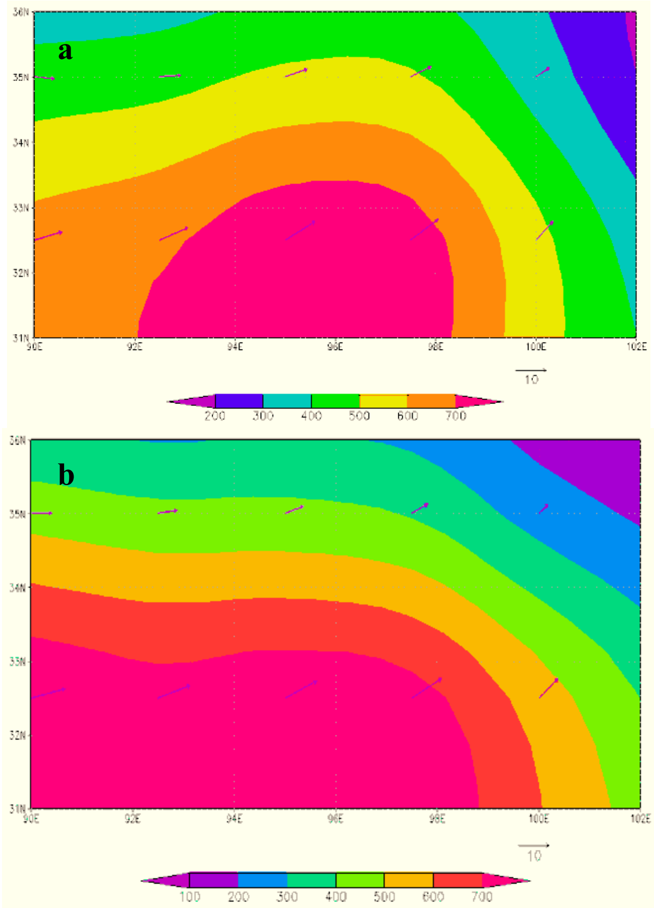

Figure 7. Distributions of water vapor fluxes at 850 hPa geopotential height in typical driest year (a) and wettest year (b) in the SRYR.

5. Conclusions

Based on long-term hydro-meteorological and reanalysis data, this research investigated multiscale variations of hydro-meteorological factors and its links to large-scale atmospheric circulation characteristic indices during 1957~2012 in the SRYR. The Mann-Kendall method and wavelet analysis method are employed to analyze the multiscale characteristics of trend and periodicity in hydro-meteorological factors. The links between hydro-meteorological factors and large-scale atmospheric circulation characteristic indices are investigated by linear correlation and cross-wavelet analysis methods. The driving effects of large-scale atmospheric circulation systems on hydro-meteorological factors were further revealed by the analysis of water vapor fluxes in the SRYR. The following conclusions were drawn:

(1) The overall trends in streamflows and precipitation were increasing, but the decadal changes had volatility. The amounts of streamflows and precipitation in the SRYR

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declined during the 1990s. Since the 2000s, the amounts of streamflows and precipitation had increased significantly.

(2) The change trends of precipitation and streamflows in the SRYR are synergetic at annual and seasonal scales. The annual average precipitation and streamflows in the SRYR have three significant periods, namely 3~5 years, 15-20 years and 30-40 years.

(3) The SAM plays a relatively more important role in the hydro-meteorological factors changes in the SRYR. During the driest (wettest) year, the SAM is relatively weak (strong), and brings less (more) southwest airflow into the SRYR, less (more) precipitation and streamflows will be generated in the SRYR.

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