Journal of Marine Science and Technology

Volume 24 | Issue 2 Article 27

ASSESSMENT ON LONG-TERM FLUCTUATIONS OF RUNOFF AND ITS CLIMATE DRIVING FACTORS

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Recommended Citation
Zhang, Hong-Bo; Huang, Wen-Cheng; Xi, Qiu-Yi; Wang, Bin; and Lan, Tian (2016) "ASSESSMENT ON LONG-TERM FLUCTUATIONS OF RUNOFF AND ITS CLIMATE DRIVING FACTORS," *Journal of Marine Science and Technology*: Vol. 24: Iss. 2, Article 27.
DOI: 10.6119/JMST-015-0521-6
Available at: https://jmstt.ntou.edu.tw/journal/vol24/iss2/27

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Acknowledgements

This work was supported by the National Natural Science Foundation of China under Grant No. 51379014, the Natural Science Basic Research Plan in Shaanxi Province of China under Grant No.2014KJXX-54, and by the Fundamental Research Funds for the Central Universities under Grant No. 310829152018 and 2013G1502044 and the Open Research Fund of the State Key Laboratory of Simulation and Regula-tion of Water Cycle in River Basin under Grant No. IWHRSKL-201109. Cordial thanks are extended to the anonymousreviewers and the editor-in-chief for their valuable comments and suggestions, which greatly improved the quality of this paper.

Journal of Marine Science and Technology, Vol. 24, No. 2, pp. 329-337 (2016)
DOI: 10.6119/JMST-015-0521-6

ASSESSMENT ON LONG-TERM FLUCTUATIONS OF RUNOFF AND ITS CLIMATE DRIVING FACTORS

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Key words: runoff, fluctuation, Hilbert-Huang transform, wavelet analysis, Jing River.

ABSTRACT

The Jing River is the largest tributary of the Wei River in northwestern China. Studying the long-term characteristics of its runoff is of significance to water resources planning and management as well as the design of hydraulic engineering activities at the local and Wei River basin scales in the present and future. Several methods were utilized in this study to investigate the long-term fluctuations in runoff for the Jing River, including continuous wavelet analysis, the Hilbert-Huang transform and correlational analysis. Furthermore, the responses of runoff to various climatic and meteorological factors including precipitation, evaporation, solar activity and the El Niño-Southern Oscillation (ENSO) phenomenon were also studied. The results indicate that the river's annual runoff exhibits multi-timescale fluctuation characteristics with a cycle of 2-4, 6-8 and 22-24 years, where the 22-24 year cycle oscillation being the first main period. The primary drivers of runoff fluctuations are climate changes, with precipitation the main driver of the 2-4 year's fluctuation and solar activity & ENSO dominant for the 22-24 year period. Though runoff exhibits a significant response to the ENSO phenomenon, it lags behind ENSO by 5 years. This delay may occur as a result of Pacific-Asian atmospheric teleconnection transmitting some information on ENSO to Asia.

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I. INTRODUCTION

Runoff is an important source of replenishment for surface and groundwater storage and is declining in most rivers that are heavily influenced by human activities and/or global climatic change (Smith and Richman, 1993; Vitousek et al., 1997; Vörösmarty et al., 2000; Guo and Li, 2012). These declines have caused many issues in recent decades, such as shortages of fresh water, water pollution, flood disasters and channel sedimentation (Douglas et al., 2000). Hence, river discharge changes and potential impacts of climatic change are of high interest all over the world (Vogel et al., 1999; Jones et al., 2006; Yang and Zhang, 2010; Zhan et al., 2012). Identifying the fluctuation characteristics in long-term runoff data has become a major priority in hydrologic sciences, as the identification of long-term hydrologic principles contained in hydrologic time series could serve to predict the outcomes of complex hydrological processes (Kantelhardt et al., 2003). At present, long-term fluctuations in river discharge have been used to study climate variability and climate change impacts (Amarasekera et al., 1997) and also serve as an important tool for detecting any modifications to hydrological systems and for regional water resources management (NRC, 1991; Chang, 2007; Bae et al., 2008).

Periodicity, also termed runoff fluctuation, was well known by Williams (1961), who investigated the nature and causes of cyclical changes in hydrological data of the world. Several different oscillation periods including 2.6, 3.5, 5, 13-14, 26-28, and 37 year cycle have been identified by various authors in precipitation and discharge time series (Brazdil and Tam, 1990; Walanaus and Soja, 1995; Kane, 1997; Smith et al., 1997; Sosedko, 1997; Lukjanetz and Sosedko, 1998; Timuhins et al., 2010). The periodicity of river discharge changes has previously been explained with the Hale cycles (11 and 22 years), Gleissberg solar activity cycles, solar-lunar tidal periods as well as other periodically occurring processes (Probst and Tardy, 1987; Currie, 1996; Vasiliev et al., 2002). In recent years, fluctuations in runoff may be related primarily to global climate patterns (Pekárová and Pekar, 2004) such as the

Southern Oscillation (SO) over the Pacific (Rodriguez-Puebla et al., 1998), North Atlantic Oscillation (NAO) over the Atlantic Ocean (Hurrell, 1995; Stephenson et al., 2000), El Niño over the Asia-Pacific region (Cluis, 1998) and ENSO (Yang and Zhang, 2010). Certainly there also exist other natural factors that influence or reinforce runoff variability.

Some previous studies have studied runoff fluctuation and its relationships with the ENSO and solar activity in China. Wang and Li (1990) demonstrated that there is a significant correlation between precipitation and ENSO in Northern China, with the former lagging the latter by 2-5 months in the southern part. Zhang et al. (2007) used the continuous wavelet transform, cross-wavelet and wavelet coherence methods to draw the conclusion that there is an out-of-phase relationship between the annual maximum streamflow of the Yangtze River and ENSO. The annual maximum streamflow is more influenced by climatic variability over longer periods and by other factors, e.g., human activities, over shorter periods. Li et al. (2009) applied a complex Morlet wavelet to study the relationship between runoff and the relative number of sunspots based on 304 years of annual natural runoff observations at the Sanmenxia station located in the Yellow River. The results indicated obvious periodic characteristics in runoff at scales of 3, 26, 46, 68 years. From a long-term period view, there is no notable correlation between natural runoff and the relative number of sunspots, but evident correlations exist within a short-term period.

The aim of this paper is to perform a long-term runoff fluctuation analysis of the discharge time series dataset for the Jing River. The selected river is the primary tributary of the Wei River and a second-order tributary of the Yellow River, running through the central region of the Loess Plateau. It is located in a transition area of semi-humid to semi-arid climate in the temperate zone, which is not only an area sensitive to climate change and an ecologically fragile zone but also a key area for soil and water conservation in the upper and middle Yellow River (Suo et al., 2008). In the past 50 years, the mean annual precipitation, actual evapotranspiration, and runoff for this area have undergone obvious reductions (Qiu et al., 2008), and the change in runoff has greatly influenced the water resource supply for agriculture as well as regional water security. Therefore, a quantitative understanding of the long-term fluctuations in Jing River runoff has become an urgent demand for local synthetical utilization of water resources and regional economic development.

Long-term changes in river discharge have been paid great attention by global scholars and governments, and some similar studies have been conducted on the Yellow River and Wei River in recent years (Fu et al., 2004; Li et al., 2004; Liu and Zheng, 2004; Yang et al., 2004; Cong et al., 2009; Miao et al., 2011; Guo and Li, 2012; Du and Shi, 2012; Gao et al., 2013; Fan et al., 2013). However, few studies have focused on the Jing River, especially on long-term hydrological fluctuations. In our previous studies, it was been found that human activities have a smaller impact on hydrological long-term

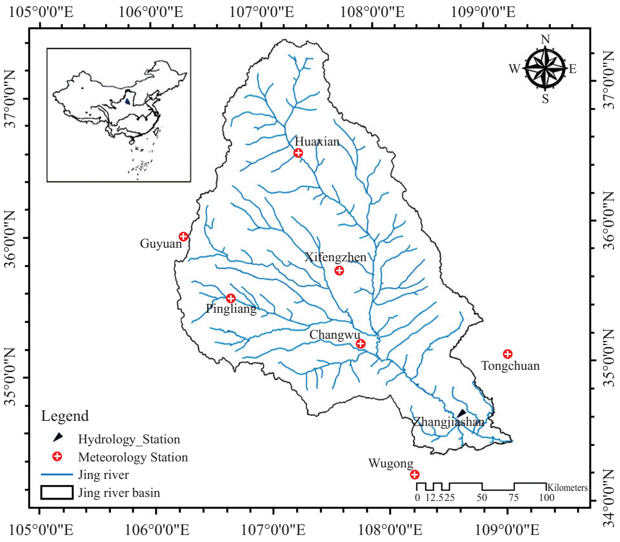

Fig. 1. Location of the study region, hydrologic and meteorological stations in the Jing River basin.

fluctuations (Zhang et al., 2015). Thus, the long-term fluctuations in river runoff will be discussed in detail, and the relationships between these changes and oscillations in climatic factors be a focus of this research. Through these discussions, the current study will be helpful for further understanding long-term changes in river runoff and will contribute to formulating future-oriented water resource management strategies for the Jing River and Wei River.

II. STUDY AREA AND DATA

1. Study Area

The Jing River catchment lies in the upper and middle reaches of the Yellow River (Fig. 1) and includes 31 counties and cities in Shaanxi, Gansu and Ningxia provinces, covering a drainage area of approximately 45,421 km^2 with administrative boundaries ranging from 105°49′ - 108°58′E and 34°14′-38°10′N. The river originates in the eastern Liupanshan piedmont in Ningxia province and flows into the Wei River at Gaoling in Shaanxi province, with a mainstream length of 455 km. The topography of the watershed is high in the northern part and low in the southern part, averaging approximately 1,200 m above mean sea level. The river network in the Jing River basin is developed, including many tributaries such as the Malian, Pu and Hong streams as well as more than 10 other streams, all cutting deeply into the loess landscape. Annual mean temperature in the basin ranges from 8-13°C. Annual average precipitation is approximately 500 mm.

2. Data

The Zhangjiashan hydrologic station (108°36′E, 34°38′N), with a drainage area of 43,216 km^2, was selected as the research station in this study. The station is the last hydrological station on the Jing River, controlling 95.1% of the total basin

Table 1. Information on the meteorological stations analyzed in this study.

Station name	Station No.	Elevation (m)	Longitude (E°)	Latitude (N°)
Guyuan	1	106.27	36	1753
Pingliang	2	106.67	35.55	1346.6
Huanxian	3	107.3	36.58	1255.6
Xifengzhen	4	107.63	35.73	1421
Changwu	5	107.8	35.2	1206.5
Wugong	6	108.22	34.25	447.8
Tongchuan	7	109.07	35.08	978.9

(as Fig. 1). The data series used in the study includes a 46-year dataset of annual and monthly measured runoff (1960-2005) obtained from the Hydrology and Water Resources Bureau of Shaanxi Province. Meteorological data for the same period, including precipitation and evaporation, were recorded at the Huanxian, Pingliang, Xifengzhen and Changwu meteorological stations in the basin and at the nearby Guyuan, Wugong and Tongchuan meteorological stations; these data were obtained from the National Climate Center of China (as Fig. 1 and Table 1).

Sunspot data were obtained from the National Climate Center of China, and multivariate ENSO index (MEI) data (a parameter describing the strength of ENSO, where the MEI index rises as the intensity of the Nino phenomenon increases) were acquired from the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) in the United States.

III. METHODOLOGY

1. Wavelet Analysis

Wavelet analysis (WA) is a signal processing method developed from the Fourier transforms that can effectively diagnose a signal's main frequency component and abstract local information from a time series depending on its good time and frequency multi-resolution (Daubechies, 1988; Meyer, 1993; Kumar and Foufoula-Georgiou, 1997). The major advantage over the Fourier method is that WA is scale-independent and, with no need for a predetermined scale, is suitable for both stationary and non-stationary datasets (Kaiser, 1994). It is more appropriate for hydrological time series with a wide range of possible dominant frequencies (Daubechies, 1990; Gaucherel, 2002; Coulibaly and Burn, 2004; Ren et al., 2011) and can be used to investigate detailed temporal patterns in both the frequency and time domains by adjusting the time and frequency signals. Recently, the continuous wavelet transform (CWT) based on the Morlet function (Morlet et al., 1982; Torrence and Compo, 1998) has been widely used to identify periodic oscillations of signals (Werner, 2008). Thus, the Morlet function was chosen as the mother wavelet function to detect local temporal patterns in this study, which is given as follows (Mallat, 2009):

$$\phi(\mathrm{t}) = \pi^{-1/4} e^{ict} e^{-t^2/2} \tag{1}$$

where $\phi(t)$ is the Morlet wavelet function; i is the imaginary symbol of a complex number; c is the non-dimensional frequency, here taken to be 6 to satisfy the admissibility condition (Torrence and Compo, 1998); and t is time.

Assume that one has a time series, X_n, with $t = 0\ldots n$, then wavelet variance can be calculated by

$$Var(a) = \int_{-\infty}^{\infty} \{W_n(a,b)\}^2 \, db \tag{2}$$

$$W_n(a,b) = |a|^{-\frac{1}{2}} \int_{-\infty}^{\infty} X_n(t) \phi^*(\frac{t-b}{a}) dt \tag{3}$$

where $Var(a)$ is wavelet variance; W_n (a, b) is the wavelet transform coefficient and can represent the characteristics of signal change at different time scales; $\phi^*(t)$ is the complex conjugate of $\phi(t)$; a is a scaling parameter that measures the degree of compression or scale; and b is the time shift or translation parameter, which determines the time location of the wavelet.

Because the wavelet variance is proportional to the duration and squared amplitude of the frequency component, we can also estimate the energy oscillation of the signal with the frequency a by calculating Var (a). Since wavelet variance denotes the distribution of wavelet energy by scale (period), we can identify all of the periodic components of the time series by seeking all of the maximums of wavelet variance, among which the domain predominant periods of one time series can be obtained from its extreme values (Gao et al., 2013). Moreover, by analyzing the wavelet coefficients W_n (a, b) at scale a in the wavelet coefficient contour map, we can obtain the dry-wet periodicity of a runoff series at scale a and further identify all dominant periods at multiple timescales. The intensity at each point in the contour map represents the magnitude of the wavelet coefficients.

2. Hilbert-Huang Transform Method

The Hilbert-Huang Transform (HHT) developed by Huang et al. (Huang et al., 1998) is an approach associating empirical mode decomposition (EMD) and the Hilbert transform for detecting changes in the variability scales and dealing with nonlinear and non-stationary data. More specifically, HHT uses the Empirical Mode Decomposition (EMD) method to decompose a signal into a collection of the Intrinsic Mode Functions (IMFs), then uses the Hilbert Spectral Analysis (HSA) to obtain instantaneous frequency data. In hydrologic science, HHT has been already applied to hydrological variability, flow fluctuation and sediment transport characteristics, and some improvements have been proposed (McMahon et al., 2008; Lee and Ouarda, 2010; Wu and Huang, 2011; Kuai and Tsai, 2012; Massei and Fournier, 2012). In this study, we apply this method to a nonlinear hydrological time series, including the decomposition of the time series considered in IMFs by EMD and the determination of the time-varying instantaneous frequency associated with each IMF by HSA. We here used the HHT Matlab program provided by Wu and Huang (2011).

EMD uses the sifting process to extract IMFs, which represent the analyzed signal at different scales, in an efficient and adaptive mode. The sifting is repeated to extract a series of IMFs. Sifting is completed when the last component is monotonic (only one maximum and one minimum). Here, IMFs satisfy the following two conditions: (a) the difference between the number of local extrema and the number of zero-crossings must be zero or one; (b) the running mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

Through the calculation of the EMD, the original time series data become the sum of n IMFs and a final residual. Now, one can apply the associated HSA to each IMF component to extract the energy-time-frequency information from the hydrological data. Finally, we can make the time frequency image based on the relationships among amplitude function, instantaneous frequency and time and gain the corresponding Hilbert spectrums. For more details about the EMD and HSA method, we refer to Huang et al. (1998, 1999, 2003), Rilling et al. (2003), Wu and Huang (2011) and Kuai and Tsai (2012).

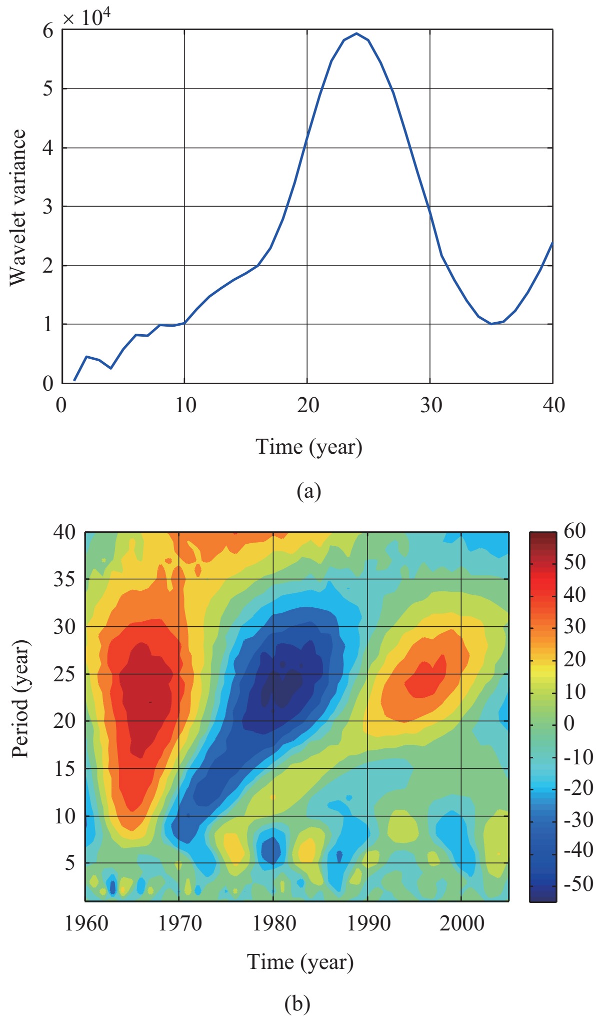

Fig. 2. Wavelet variance (a) and real part wavelet coefficient contour map (b) of the measured runoff time series at Zhanjiashan hydrological station.

IV. RESULTS AND DISCUSSION

1. Hydrologic Cycle Identification

We selected a realistic annual runoff time series (from 1960 to 2005, approximately 46 years) as the computing data series and conducted the wavelet analysis as well as the Hilbert-Huang transform method to investigate the multi-time scale laws of the series.

Wavelet analysis The characteristics of the hydrologic cycle at the Zhangjiashan station were studied using the CWT. The obtained results, illustrated in Fig. 2, reveal that the annual runoff of the Jing River exhibits multi-timescale fluctuation characteristics, with three periods of approximately 24a, 6-8a and 2-3a. Of these periods, 24a is the first main oscillation. Moreover, looking over a long time scale, the two time periods of 1960-1972 and 1988-2002 were located in the positive phase, in which the volume of runoff is relatively abundant. Conversely, the time periods of 1973-1987 and the years after 2000 fall in the negative phase, in relatively dry periods. The wavelet coefficient distribution also reveals that the 6-8a oscillation begins to stabilize from 1976 onwards and is longer after 1997.

Hilbert-Huang transform To verify the accuracy of the multi-time scale characteristics revealed for Jing River runoff, we also applied the HHT method to analyze that annual flow time series (m^3/s), as shown in Fig. 3. Apparently, the annual runoff series can be split into 4 intrinsic mode functions and 1 residual trend. With increases in the degree of IMF components as well as the deduction of frequency variations, the wave shapes become more simple and neat, while the non-stationarity of the series decreases. What is more, the residual trend exhibits a marked decrease. Through Hilbert Spectral Analysis, we obtained the IMF central frequencies of the annual runoff series for the Jing River from low to high orders, as 0.3936, 0.2927, 0.1523 and 0.0435, successively. The corresponding periods are 2.54a, 3.42a, 6.56a and 22.97a, respectively, which roughly manifests that there are three periods of 2-4a, 6-7a and 22-23a in Jing River runoff, which is basically consistent with the results obtained from the CWT.

From the above results, we eventually confirmed that there are hydrological oscillations (periods) of 2-4a, 6-8a and 22-24a in the runoff of the Jing River, of which 22-24a is the first main period. This conclusion is basically similar to the periods iden tified for its mother river, the Wei River, which

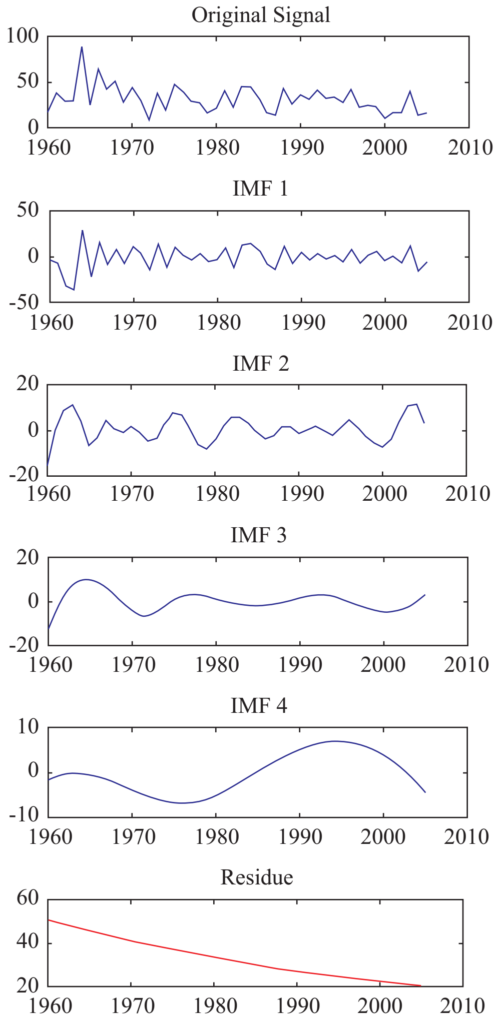

Fig. 3. Decomposition diagram of the realistic runoff time series at Zhangjiashan Station on the Jing River.

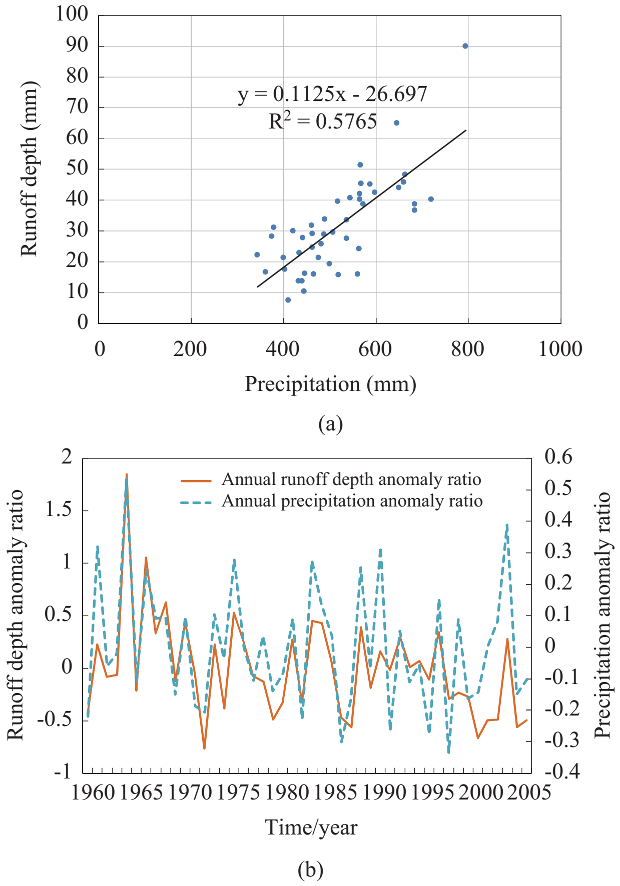

Fig. 4. Correlation analysis between precipitation and runoff depth.

experiences hydrological cycles of 2-4a, 6-8a, 9-11a and approximately 22a. This finding about the first main period is also roughly compatible with that for the Yellow River (Liu et al., 2003).

Based on the main oscillation, it is clear that the time period from 2010-2018 should fall within the increasing period of the main oscillation, when relatively abundant flow occurs. Meteorological factors as cycle drivers Numerous studies have investigated how long-term change in runoff is influenced by meteorological factors such as precipitation and evaporation (Cluis, 1998; Bae et al., 2008). To better comprehend the re- lationships between the runoff time series and meteorological variations and to identify the driving forces of runoff fluctuations, we also analyzed the time series of annual precipitation and evaporation from 1960 to 2005 at the Zhanjiashan station.

Correlation analysis of precipitation and runoff Through the correlation analysis between precipitation and runoff depth (Fig. 4(a)), we find a good significant correlation between them with a correlation coefficient of 0.76. Meanwhile, according to their double mass cumulative anomaly curve (Fig.4(b)), we also observe a strong similarity in plentiful and withered circulation as well as periodicity between the runoff and precipitation series. Though the difference in the accumulative curve became greater after 1991, their variation trends have stayed roughly the same.

2. Fluctuations of Meteorological Factors

The continuous wavelet transform was again used in the study to address precipitation and evaporation series and analyze their multi-timescale variation features. Figs. 5 and 6 illustrate the changes in wavelet variance and the wavelet coefficient distribution of the two series in the Jing River basin. From the following figures, we find that the periods of the precipitation series are approximately 3, 6, 11, 15 and 25-26a, respectively, and that the periods of the evaporation series are 6, 11, 15 and 25-26a. In conclusion, there are evident fluctuation features in precipitation and evaporation in the studied basin, both with fluctuations over 6, 11, 15 and 25-26a. The first main period for both of these series is also the same at 25-26a.

By contrasting the results of the fluctuations of runoff, precipitation and evaporation (Table 2), it is clear that they have

Table 2. Periods of precipitation, evaporation and runoff series at Zhangjiashan station.

Series	Period 1	Period 2	Period 3	Period 4	Period 5
Precipitation	3	6	11	15	25-26
Evaporation		6	11	15	25-26
Runoff	2-4	6-8			22-24

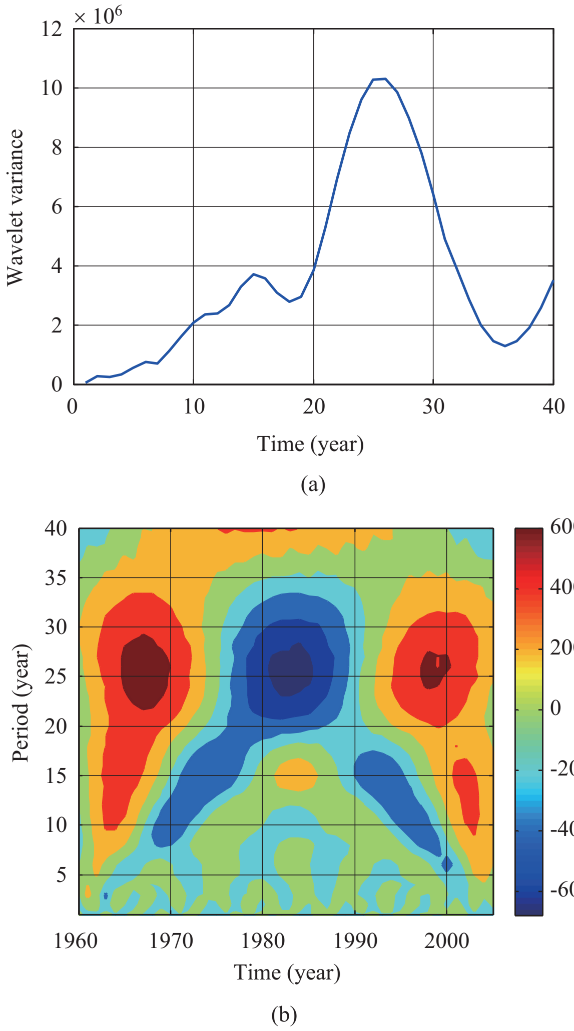

Fig. 5. Wavelet variance (a) and real part wavelet coefficient contour map (b) of precipitation series in the Jing River basin.

roughly similar multi-timescale laws, especially at the scales of 2-4, 6-8 and 22-26a.

To further explore the driving of runoff by meteorological factors, we constructed correlation diagrams among the IMFs of precipitation, evaporation and runoff with the same or similar frequencies. The results indicate that the oscillations of precipitation and evaporation on different time scales do not exhibit a very good correlation, except for that of IMF1 with runoff. Their change process on IMF1 is presented in Fig. 7, representing 2-4a cycle between precipitation and runoff. Thus, we generally believe that the hydrological fluctuations in the runoff series have far-reaching effects on the 2-4a timescale by precipitation and no significant effects on other scales.

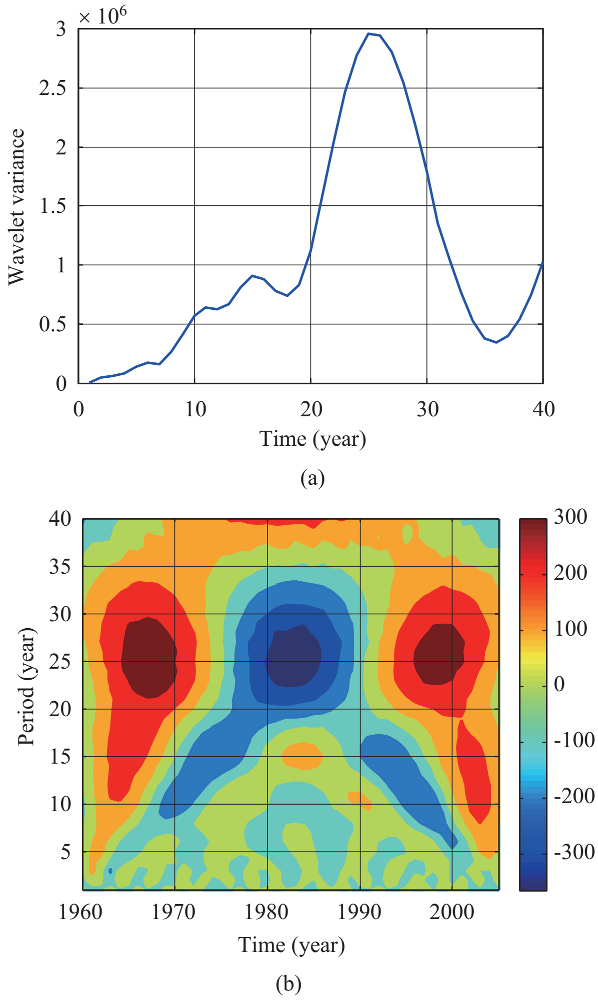

Fig. 6. Wavelet variance (a) and real part wavelet coefficient contour map (b) of evaporation series in the Jing River basin.

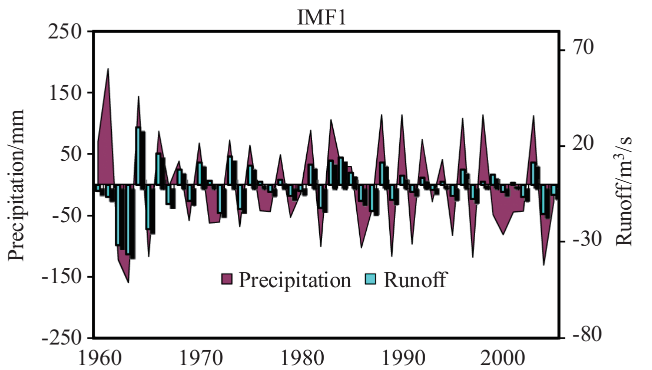

Fig. 7. IMF1 change process of precipitation and runoff.

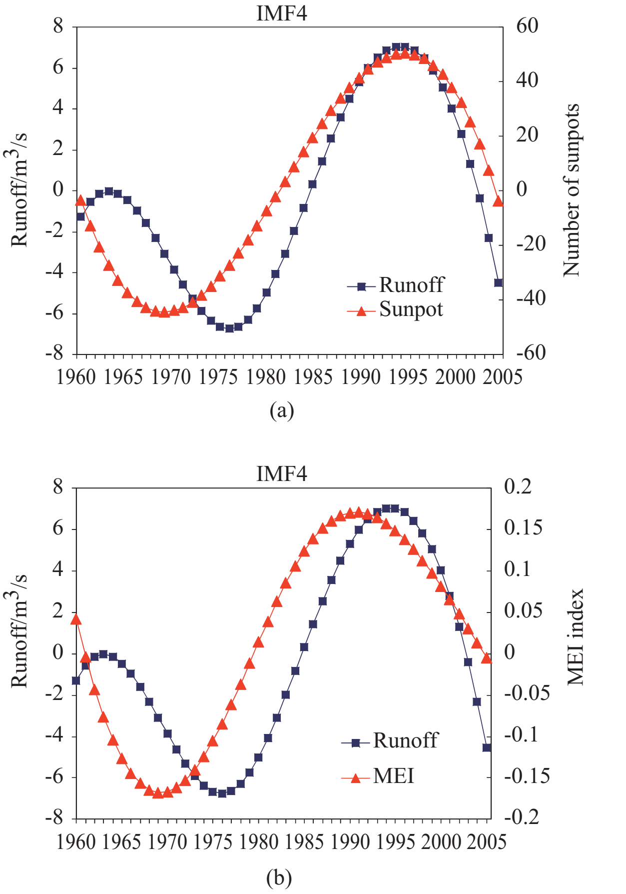

Fig. 8. Correlation diagrams of number of sunspots (a) and the MEI index (b) with runoff.

3. Climate Factors as Cycle Drivers

The annual mean data on sunspot numbers and the MEI index were decomposed by EMD, and 4 IMFs and a residue were obtained separately. We produced correlation diagrams with similar IMFs for runoff and found only one very good relationship on IMF4 (22-24a) among them, presented in Fig. 8. Many previous studies have demonstrated that solar activity exhibits 11- and 22-year oscillations (Beer et al., 1988; Gladysheva et al., 2002), indicating that it may be related to the oscillation of the Jing River runoff. In previous studies, runoff period variation is noted to correlate strongly with the ENSO phenomenon (Simpson et al., 1993; Dettinger and Diaz, 2000). As indicated in Fig. 8b, it is known that the ENSO phenomenon exhibits a similar oscillation with runoff on 22-24a scales, the latter lagging behind the former by 5 years. These findings raise the possibility that runoff variation is dominated by solar activity and ENSO on 22-24a time scales.

Moreover, we have uncovered an interesting phenomenon in this study, i.e., that the decomposed residue of evaporation is more strongly related than runoff with that of the MEI index, as shown in Fig. 9. It is obvious in the figure that evaporation decreases with a rising MEI index, then increases as the MEI index decreases after 1990s. This is perhaps evidence that the impact of ENSO warm events on climate changes in the Northern China is significant.

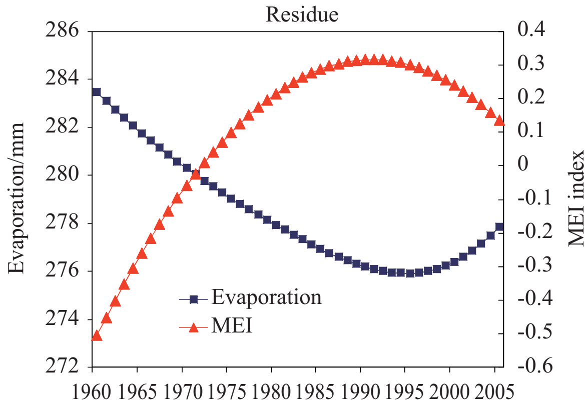

Fig. 9. Correlation diagram of the decomposed residues from the MEI index and evaporation.

V. CONCLUSION

As revealed by this study, the long-term fluctuation of Jing River runoff exhibits the following characteristics: (a) The annual mean runoff series presents multi-timescale fluctuation characteristics, with a cycle of 2-4, 6-8 and 22-24 years, among which 22-24 year cycle is the first main period. Based on this main oscillation, we consider that the time period from 2018-2025 should be a period of relatively plentiful discharge. (b) Climate changes have dramatic influences on runoff evolution in the Jing River. Precipitation primarily drives the 2-4 year's hydrological fluctuation in the runoff series, and the 22-24 year period is perhaps influenced by solar activity and ENSO. The ENSO phenomenon in particular exhibits a very similar oscillation to that of runoff, with runoff lagging 5 years behind ENSO. This may be due to Pacific-Asian atmospheric teleconnection, which transmits some information on ENSO to Asia.

In addition, we observed a pattern between ENSO and evaporation in the study, which is that the change trend of evaporation is significantly negatively correlated with that of the MEI index. Evaporation decreases as the MEI index rises before 1990 and increases as the MEI index decreases after that year. This finding may be evidence that ENSO warm events significantly affect Northern China.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under Grant No. 51379014, the Natural Science Basic Research Plan in Shaanxi Province of China under Grant No.2014KJXX-54, and by the Fundamental Research Funds for the Central Universities under Grant No. 310829152018 and 2013G1502044 and the Open Research Fund of the State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin under Grant No. IWHR-SKL-201109. Cordial thanks are extended to the anonymous reviewers and the editor-in-chief for their valuable comments and suggestions, which greatly improved the quality of this paper.

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