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Streamflow changes of the Changjiang (Yangtze) River in the recent 60 years: Impacts of the East Asian summer monsoon, ENSO, and human activities

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ABSTRACT

Streamflow in the Changjiang River has experienced significant changes in recent decades due to the coupling of environmental factors and intensive anthropogenic activities in associated catchments. Based on a long-term data set, including water discharge, precipitation, temperature, East Asian Summer Monsoon (EASM), El Niño – Southern Oscillation (ENSO), and reservoir volumes in the most recent 60 years, the modes of streamflow changes along the Changjiang and associated factors was discussed. Analysis of streamflow observations by empirical mode decomposition show that streamflow along the Changjiang consist of a trend and four intrinsic components. Trend component in streamflow had obvious downward changes, which could be mainly attributed to dam construction. In addition, increased snowmelt caused by a warming climate led to more water being discharged into the upper reaches. The resultant intrinsic component of streamflow changes can be characterized by two modes using empirical orthogonal function analysis. The main mode represents periodic oscillations in baseflow due to the coupling of a weak EASM and weak ENSO. The secondary mode reflects differences in streamflow changes between the upper and lower reaches of the Changjiang River, which is anti-phased relative to changes in streamflow between the upper and lower reaches. These differences may be caused by a weak EASM and intensive ENSO. Moreover, the combination of a weak EASM and ENSO can lead to extreme flood. Extreme drought years may be significantly impacted by intensive EASM and ENSO.

1. Introduction

The availability of water resources is a globally important issue for human development. However, water discharges have been influenced by climate change, which could further impact water availability for humans. In recent decades, intensive human activities (e.g., irrigation, dam construction, etc.) have had major impacts on river water discharge, including the magnitude, hydrology, and high and low flows (Walling and Fang, 2003; Magilligan and Nislow, 2005; Dai et al., 2008; Syvitski et al., 2009; Xue et al., 2011). In addition, the hydrologic characteristics of the global water system show periodic oscillations or time shifts due to climate fluctuations in catchment areas (Pekárová et al., 2003). The coupling of climate variations and anthropogenic activities has affected the flow regulation of major rivers world-wide (Lu, 2004; Nilsson et al., 2005; Vörösmarty et al., 2010), with downstream impacts on estuarine ecology (e.g., Dai et al., 2011a; Gong et al., 2012). Therefore, there is increasing concern about the impacts of climate change and anthropogenic perturbations on changes in the streamflow of rivers (Vörösmarty et al., 2010).

The Changjiang (Yangtze) River is the longest river in Asia and one of the significant rivers world-wide. The river flows for over 6300 km from the glaciers in the Tibet Plateau eastward across southwest, central and eastern China to the East China Sea (Fig. 1). The Changjiang can be divided into upper, middle, and lower reaches at Yichang, Hukou, and Datong, respectively (Fig. 1). The river has a discharge of 960 × 10^9 m^3/y during the recent decades, and streamflow changes are significantly influenced by the East Asian summer monsoon (EASM) and ENSO (El Niño/La Niña Southern Oscillation) (Zhang et al., 2007; Wang et al., 2008; Blender et al., 2011). Asian summer monsoon is one of the large scale circulation patterns affecting the Changjiang basin, which basically determines the Changjiang basin precipitation (Duan et al., 2004; Wang et al., 2008; Blender et al., 2011). The hydrology in the upper Changjiang River is mainly impacted by the

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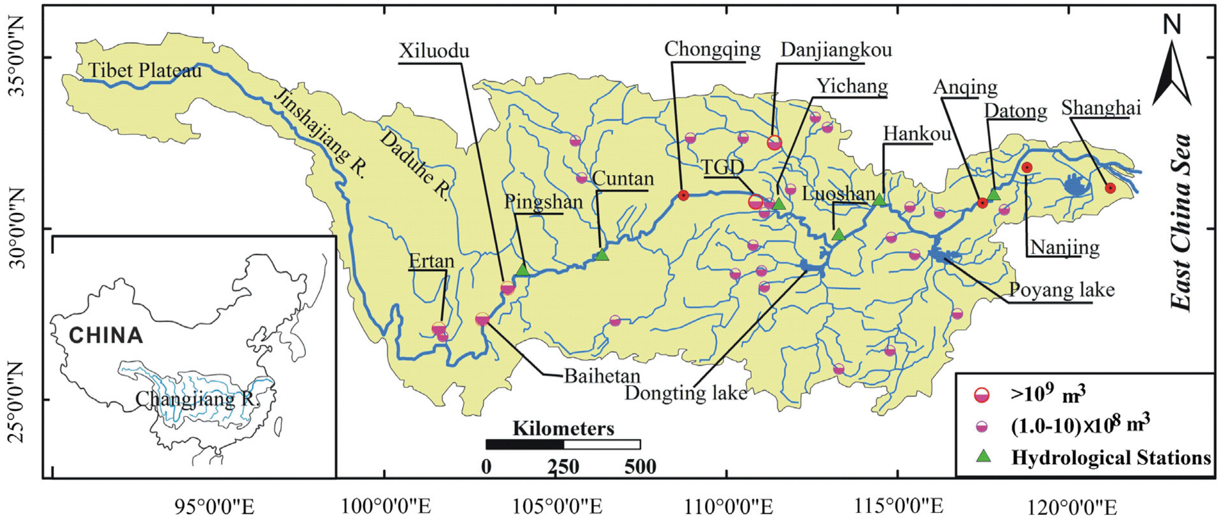

Fig. 1. Research area and distribution of gauging stations.

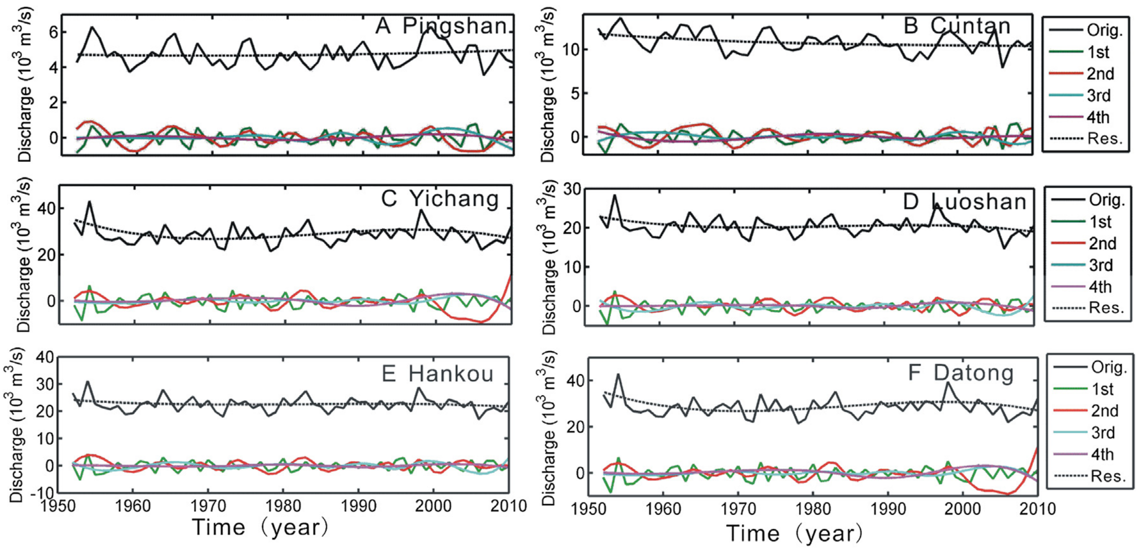

Fig. 2. Streamflow observations and decomposed modes identified using EMD (Org. surveyed original streamflow is denoted by the black line; Res: the residual part of the decomposed streamflow is denoted by the dashed line; 1st, 2nd, 3rd, and 4th: the periodic part of the decomposed streamflow with fluctuation around zero).

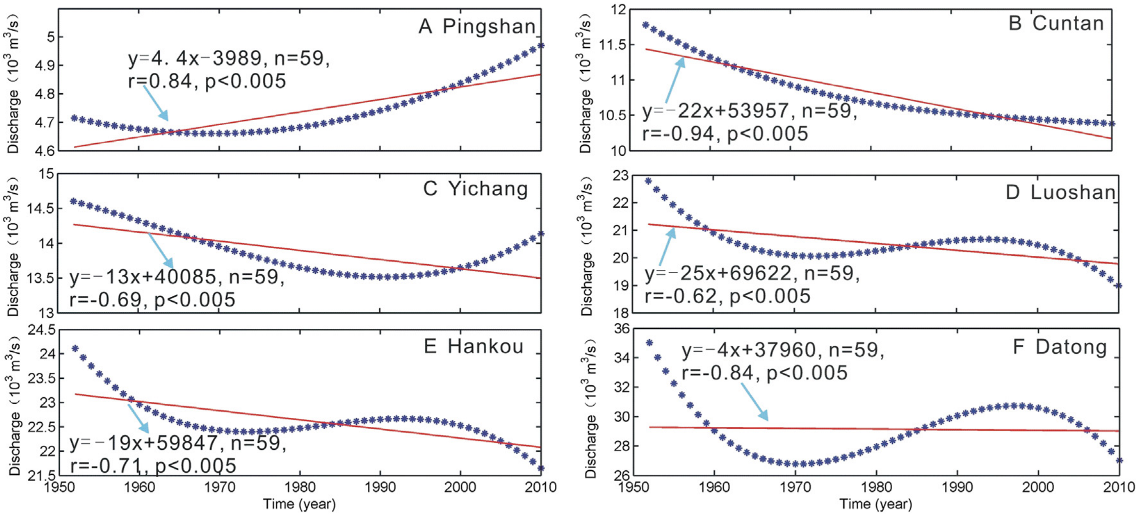

Fig. 3. Trends in the residual component of streamflow changes.

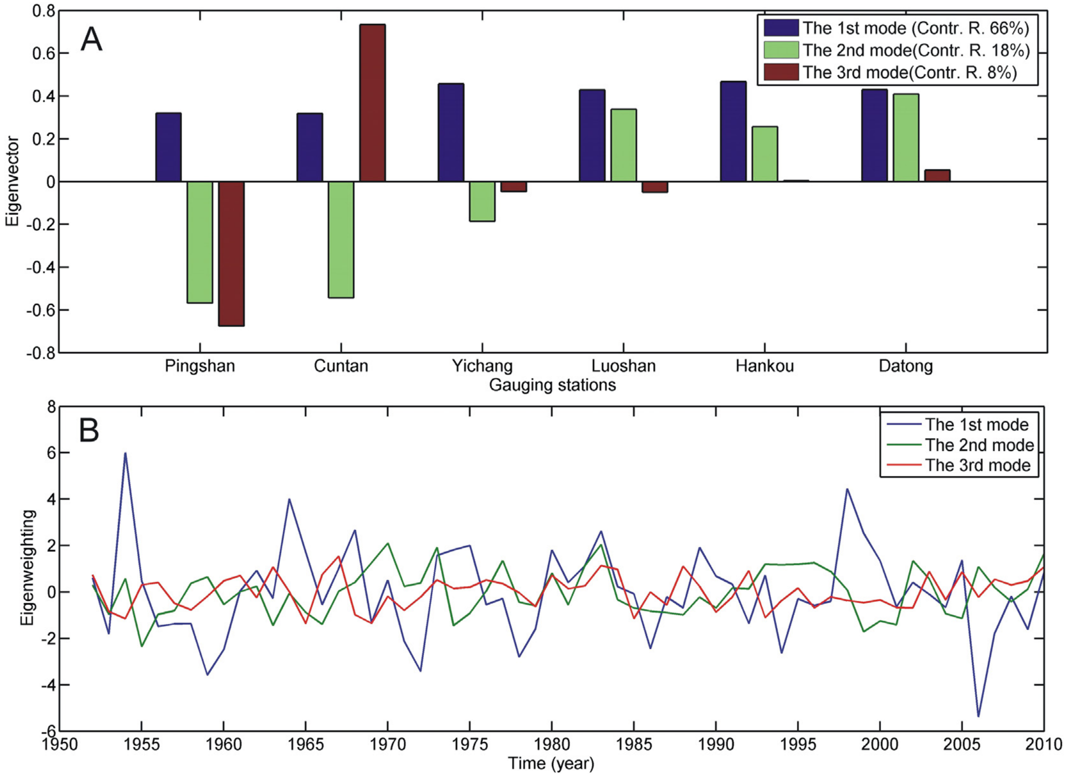

Fig. 4. Modes of the periodic component of streamflow changes determined using EOF.

Indian summer monsoon and the middle and lower reaches are mainly influenced by the EASM (Zhang et al., 2007). The ENSO reflects the dominant coupled ocean-atmosphere mode of the tropical Pacific (Cane, 1992), which is closely linked with the significant part of the global climatic changes (Trenberth et al., 1998). Different phases of the ENSO usually determines high or low river flow, and ENSO extreme phases are directly correlated with the major events of floods and droughts in many regions of the world (Amarasekera et al., 1997; Barlow et al., 2001; Jain and Lall, 2001). For example, ENSO events account for about 50% decrease in flow of the Huanghe (Yellow River, China) to the sea (Wang et al., 2006). ENSO contributed to the flow in the upper reaches of the Huanghe (Lan et al., 2002). Based on the relationships of the ENSO mode and flow of the Paraná River, Brazil, statistical forecasts of river flow are also carried out (Cardoso and Silva Dias, 2006). Effects of the ENSO on water supply in the Columbia River basin were also assessed (Barton and Ramírez, 2004). Xue et al. (2005) indicated that multi-scale variability of the river flow in China is connected with the ENSO events. In addition, previous studies show variability in streamflow of the Changjiang River in the past 50 years and under extreme drought conditions (Dai et al., 2008) and have characterized the relationship between precipitation and river flow (Zhang et al., 2005; Xu et al., 2008a, 2008b). However, few studies have evaluated the spatial variability in river flow relative to EASM, ENSO, and anthropogenic activities. In the recent decades, changes in water discharge have occurred due to the construction of over 50,000 dams in the Changjiang basin (Chen et al., 2008; Yang et al., 2011; Dai et al., 2011b; Wang et al., 2013). Therefore, the purpose of this study is to systematically examine the spatial variability in river flow of the Changjiang and discuss the related factors (EASM, ENSO, and anthropogenic activities).

2. Data and methods

2.1. Data collection

Monthly mean discharges were collected at Yichang, Hankou, and Datong along the Changjiang (Fig. 1). Yearly mean discharges were determined at various stations, including Pinshan, Cuntan, and Luoshan (Fig. 1). All discharge data are from the Yangtze River Water Conservancy Committee (YWCC), Ministry of Water Conservancy of China (www.cjh.com.cn). Water discharges at these

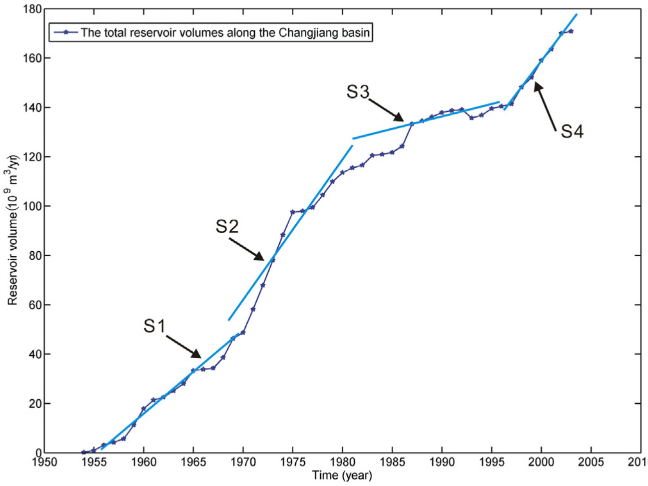

Fig. 5. Changes in reservoir volumes along the Changjiang (S1, S2, S3, and S4 is the slope of reservoir volume curves vs. year).

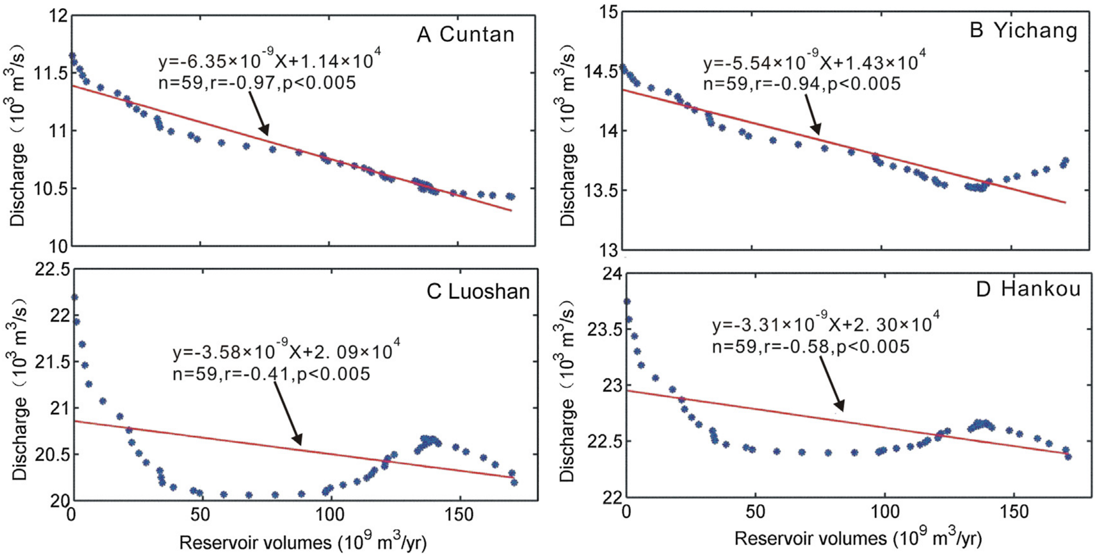

Fig. 6. Plots of the residual component of streamflow changes vs. reservoir volumes.

six stations represent streamflow changes along the Changjiang mainstem. Monthly mean temperature and precipitation records from 1952 to 2010 at Yichang, Hankou, and Anqing were obtained from the China Meteorological Administration (http://cdc.cma.gov.cn). The EASM index can be defined as an area-averaged, seasonal (June, July, and August), dynamical normalized seasonality (DNS) at 850 hPa within the East Asian monsoon domain (10°–40°N, 110°–140°E) (Li and Zeng, 2002, 2003, 2005; http://lgp.asg.ac.cn). The ENSO index is described by sea surface temperature anomalies in the Nino3 region in the eastern tropical Pacific (5°S–5°N, 90–150°W), which is available from The National Center for Atmospheric Research, U.S.A. (http://www.cgd.ucar.edu). In addition, the capacity of all reservoirs in the river basin since the 1950s was obtained from YWCC (www.cjh.com.cn).

2.2. Methods

Hilbert–Huang transform (HHT) is a method of time series analysis based on Empirical mode decomposition (EMD) and Hilbert spectral analysis that is capable of dealing with non-stationary, nonlinear time series problems (Huang and Wu, 2008). Empirical mode decomposition (EMD) is the key component of HHT, and any

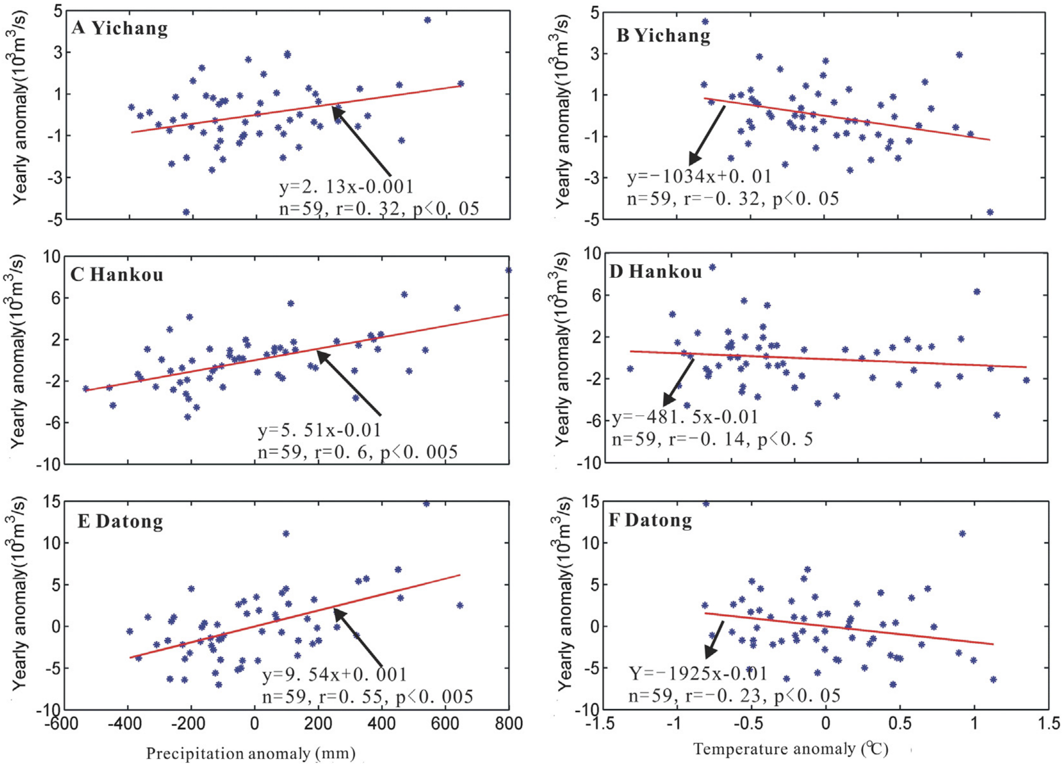

Fig. 7. Plots of the annual anomalies in streamflow vs. precipitation and temperature.

complicated data set can be decomposed using EMD into a residual component and small number of intrinsic mode functions (IMFs) (Loh et al., 2000; Huang and Wu, 2008). In comparison with the previous signal analysis methods, the EMD method is adaptive and it has been widely applied in geophysical research (Loh et al., 2000; Vasudevan and Cook, 2000; Zhang et al., 2003; Duffy, 2004; Huang and Wu, 2008). The purpose of EMD is to decompose signals into series of IMFs and a residual, which can be described as follows (Huang and Wu, 2008):

$$X(t) = \sum_{i=1}^{n} c_i + r(t) \quad i = 1, \ldots n \tag{1}$$

Where $X(t)$ is the signal to be decomposed, and c_i are the resultant IMFs. $r(t)$ is a residual component, which represents the trend existing in the signal $X(t)$ (Huang and Wu, 2008; Massei and Fournier, 2012). IMFs are oscillatory functions with varying amplitude and frequency, which represent different periodic fluctuations of the signal $X(t)$ (Huang and Wu, 2008; Song and Bai, 2012). Some studies have indicated that IMFs have a more clearly physical definition of local phase change than other non-IMF time series data sets (Duffy, 2004; Huang and Wu, 2008). Thus, EMD can be applied to nonlinear and non-stationary processes. Due to the coupling between the intensive human activities and climatic changes in the Changjiang basin in recent decades, the original streamflow records at different stations could be likely contained influence signals of both anthropogenic action and climatic changes. Thereafter, considering the impacts of complicated factors on streamflow in the Changjiang, EMD can be used to extract IMFs and residual component to subsequently analyze the periodic and trend changes in streamflow.

The resultant IMFs with periodic changes in streamflow at various stations and associated climatic factors (i.e., EASM and ENSO) were determined using the empirical orthogonal function (EOF) technique. The aim of EOF is to identify a new set of statistically independent variables that capture most of the observed variance from the original data. Eigenanalysis can separate the temporal and spatial dependence of the data by considering data as a linear combination of products of corresponding functions of time (eigenweighting) and space (eigenvectors). Eigenvectors are a special set of vectors associated with a linear system of equations (i.e., a matrix equation) that are sometimes also known as characteristic vectors, proper vectors, or latent vectors (Marcus and Minc, 1988). Here, the meanings of Eigenvectors represent the main spatial changes in streamflow of the different gauging stations. Therefore, EOF has been applied to indicate potential physical modes in recent years (Emery and Thomson, 2001; Dommenget and Latif, 2002; Liu et al., 2002; Lane, 2004; Dai et al., 2010a). Here, EOF was used to find possible modes of streamflow changes along the Changjiang and associated climate factors.

3. Results

3.1. Residual and periodic characteristics of the streamflow

The time series of streamflow from 1952 to 2010 at six stations was decomposed into five intrinsic modes using EMD (Fig. 2). The first four intrinsic modes show different characteristics with possible periodicities of 3, 7, and 11 years. However, the residual component had clear, linear upward or downward trends, except at Datong (Fig. 2). The four intrinsic modes and a residual component identified using EMD can be divided into two components: the trend change of the residual component; and the periodic component of the combination of the other four modes. Further, linear regression analysis shows a highly significant trend correlation ($p < 0.005$) between the residual component and corresponding years (Fig. 3). Increasing trends in streamflow at Pingshan and decreasing trends at Cuntan, Yichang, Luoshan, and Hankou are clear (Fig. 3). The decreasing slope in the residual component at Cuntan was larger than those at other stations, suggesting that the linear upward/downward trends for the residual component and the periodicities of the other four modes may relate to the long-term human effects and periodic climate cycles, respectively (Rao and Hsu, 2008).

3.2. Modes of streamflow changes

The residual component of the streamflow changes reflects non-periodic, linear upward or downward characteristics; thus, the combination of the periodic components, including the other four intrinsic modes, was standardized and can be decomposed into several modes using EOF. The EOF results show that the streamflow data set was highly correlated with the first three eigenmodes, which accounted for 92% of the time and space correlated

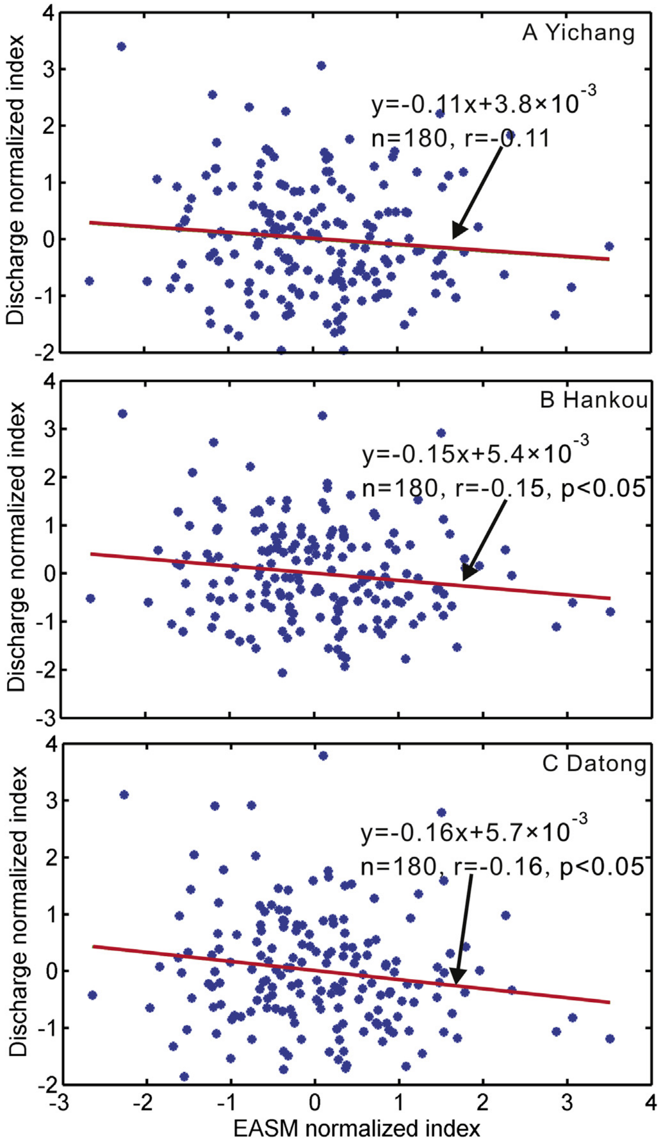

Fig. 8. Plots of the monthly anomalies in streamflow vs. the ENSO index.

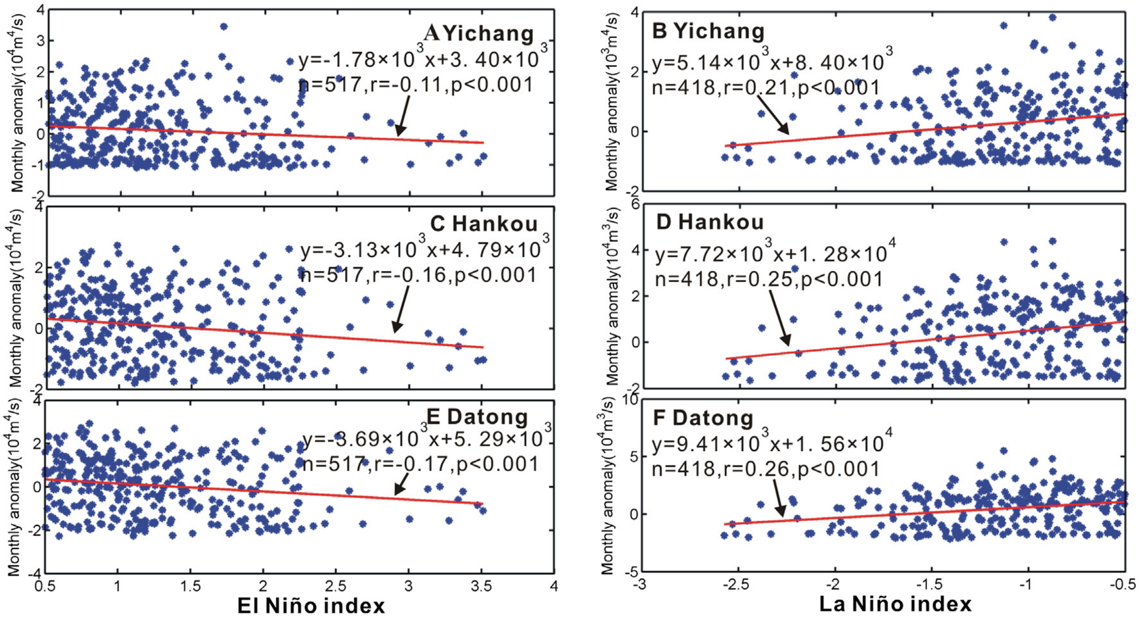

Fig. 9. Plots of the normalized indices in streamflow vs. normalized indices of EASM.

streamflow changes (Fig. 4). The remnant eigenmodes can be considered as noise and removed (Emery and Thomson, 2001; Dai et al., 2010a).

The eigenvectors of the first mode, which explains 66% of the correlations, have positive values at six stations, with gradually increasing trends from Pingshan to Datong (Fig. 4A). Eigenweighting of the first mode shows 3–7 year fluctuations, with abrupt changes in extreme flood years (1954 and 1998) and in extreme drought years (1979 and 2006) (Fig. 4B). This pattern reflects the relatively stable baseflow in the Changjiang River, where the baseflow had minor increases from the upper reach to the lower reach (Dai et al., 2010b). In other words, the first mode describes baseflow changes in the Changjiang with possible impacts from periodic climate changes.

The second eigenmode explains 18% of the correlations. The streamflow eigenvectors show that there is a clear boundary among these six stations (Fig. 4A). There are negative values at Pingshan, Cuntan, and Yichang. However, positive values were found at Luoshan, Hankou, and Datong (Fig. 4A). The temporal characteristics of this mode show subtle, periodic fluctuations (Fig. 4B). Clearly, the characteristics of streamflow changes along the Changjiang have distinct differences between the upper reaches at Yichang and lower reaches at Luoshan. The second mode suggests that there is an anti-phased relationship in upper-reach streamflows with those in the lower reaches.

The third eigenmode accounts for 8% of the correlations. The corresponding eigenvector had positive and negative values at different stations, which reflect complicated changes in streamflow. The temporal characteristics of this mode show relatively long periodic cycles compared with those of the second mode. Taken together, the third eigenmode had no obvious features, which may have been caused by synthetic climate factors.

4. Discussion

4.1. Anthropogenic impacts on streamflow changes

Anthropogenic activities, such as damming, water diversion, and agricultural and domestic consumption have affected the natural behavior of rivers since the Industrial Revolution in the 18th century (Nilsson et al., 2005). The Changjiang basin has also been affected by human activities, especially via dam construction. Over 50,000 dams have been built in the Changjiang basin, with many located in the upper reaches of the river (Yang et al., 2011). The total reservoir volume since the 1950s shows four clear stages: (1) total volume increased slowly until 1970; (2) volume increased rapidly from 1970 to 1989; (3) volume increased slowly from 1980 to 1995; and volume increased rapidly after 1995 (Fig. 5). The current reservoir volume is almost 180×10^9 m^3/y, 20% of the yearly streamflow of the Changjiang.

Although there is special attentions on impacts of reservoirs on streamflow changes in the previous researches (Xu et al., 2008a; Yang et al., 2011), no studies are related to the trend and periodic components in streamflow of the Changjiang River. Linear regression analysis between the residual component at Cuntan, Yichang, Luoshan and Hankou and reservoir volumes indicate a negative relationship, with significance level of 0.005 (Fig. 6). Thus, the trend changes in streamflow at these four stations may have been induced by dam construction. The correlation coefficients between the residual components and reservoir volumes at Cuntan and Yichang are much larger than those at Luoshan and Hankou. This pattern suggests that the numerous reservoirs (e.g., the Three Gorges Dam, located in the upper reach) in the upper reaches may have led directly to decreased streamflow (Fig. 1). However, due to the relatively small number of reservoirs located at the lower reaches and high discharge into the mainstem from the Dongting and Poyang lakes (Fig. 1), decreases in streamflow at the lower reaches, especially at Datong, show minor changes.

Increasing trends in the residual component at Pingshan may be explained by abnormal snowmelt from the Himalayas in recent years. Snowmelt plays a dominant role in the seasonal patterns of streamflow (Barnett et al., 2005). However, global climate warming due to anthropogenic activities have caused the hydrological cycle on a global scale to be greatly influenced by snowmelt (Barnett et al., 2005). Based on previous investigations, annual snowmelt is approximately 1×10^9 m^3 in the Changjiang headwaters, and the total equivalent ice area of the Changjiang headwaters amounted to 1051×10^6 m^2 in 2009. This value is approximately 196×10^6 m^2

lower than the historical record of 1247 × 10^6 m^2 (ECEP, 2009). Thereafter, rapid snowmelt of the Changjiang headwaters may increase water discharges into the upper reaches, which may be reflected in the streamflow records from Pingshan.

4.2. *EASM and ENSO impacts on streamflow changes*

4.2.1. *Precipitation and temperature*

Streamflow changes in the Changjiang should be controlled by local precipitation and temperature (Xu et al., 2008a). In this study, correlation analysis between annual streamflow and precipitation anomalies at different stations shows that the results are in agreement with previous research (Xu et al., 2008a) (Fig. 7). In addition, negative relationships between streamflow and temperature anomalies suggest that higher temperatures may induce higher evaporation and lower streamflow (Fig. 7).

Both precipitation and temperature are determined by climate change, but there have been few studies evaluating the coupling of climate and streamflow in the Changjiang River. Thus, considering that the Changjiang basin was mainly controlled by EASM and ENSO, the combination of EASM, ENSO, and the periodic component of streamflow at each station was first standardized and decomposed using EOF.

4.2.2. *EASM and ENSO*

Although the impacts of EASM and ENSO on streamflow changes of the Changjiang River had been detected (e.g. Chen et al., 2009; Zhang et al., 2005, 2007), there has been obvious lack of understanding of the impacted region of the Changjiang River by EASM

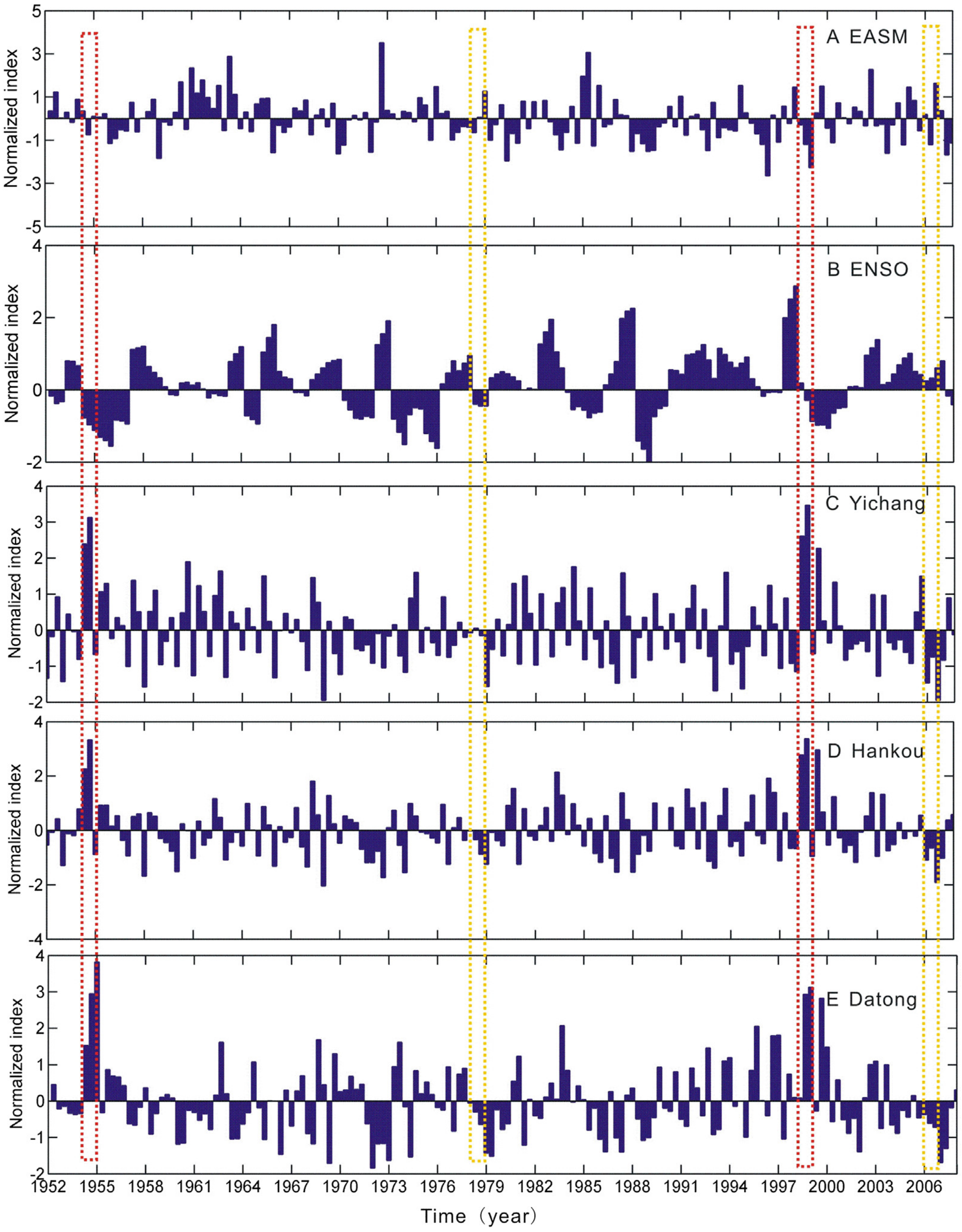

Fig. 10. Normalized indices for EASM, ENSO, and streamflow at Yichang, Hankou, and Datong.

and ENSO and what coupling of EASM and ENSO to impact on the streamflow. Variation in the normalized indexes of streamflow at Yichang, Hankou, and Datong exhibited anti-phased relationships with EASM and ENSO (Fig. 8, Fig. 9). These anti-phase relationships are clear in extreme conditions, such as the drought years of 1978 and 2006 and flood years of 1954 and 1998 (Fig. 10). When the intensity of EASM and ENSO was strong (i.e., positive values), the streamflow index at these three stations had low water discharge with negative values. However, negative values of EASM and ENSO represent a weak EASM and strong La Niña, which corresponds to heavy flooding with positive streamflow values at these stations (Figs. 8–10).

Moreover, the absolute value of the continuous 6-month running mean sea surface temperature was greater than 0 (Trenberth, 1997) with temperatures of 4 °C or below −0.4 °C can be defined as one event of El Niño and La Niña, respectively. Here, all emergence numbers of El Niño and La Niña events were calculated, and linear regression analyses between El Niño/La Niña indices and streamflow anomalies at Yichang, Hankou, and Datong were carried out. The La Niña index was positively correlated to monthly streamflow anomalies, and similar negative relationships were observed between the El Niño index and streamflow at Yichang, Hankou, and Datong (Fig. 9). Absolute values of the correlation coefficients (r) were lower (Fig. 9) in the upper (e.g., Yichang) versus lower reaches (e.g., Datong). Together, these results suggest that the ENSO impacted region in the lower reaches was larger than that in the upper reaches. Thus, impacts of El Niño events over the Changjiang basin will induce lower streamflows, while La Niña events will cause higher streamflows in this region (Chen et al., 2009).

EOF results show that the first three modes account for almost 80% of the total variance (Fig. 11). Thus, the first three modes reflect the basic coupling of EASM, ENSO, and streamflow along the Changjiang, while the remnant variances were considered as noise and removed. The first mode explained 51% of the total variance and represents the main coupling interactions between EASM, ENSO, and streamflow (Fig. 11). The eigenvector of the first mode had positive values, except for the EASM and ENSO indices. Eigenweighting of this mode shows periodic cycles of approximately 3–7 years, which is largely in agreement with the quasi-biennial oscillation of EASM and the 3–7 year oscillation of ENSO (Lau and Shen, 1988; Joseph et al., 1994). In addition, eigenvector values at the six stations in this mode were similar to those in the first mode in Fig. 4. Thus, the first mode reflects that baseflow patterns of streamflow changes were dominated by the coupling of weak EASM and ENSO passing over the Changjiang basin.

The second mode accounts for 16% of the total variance and represents the minor mode for coupling between EASM, ENSO, and streamflow. There were relatively large negative values for EASM and positive values for ENSO in the second mode (Fig. 11). However, negative values in eigenvectors at Pingshan, Cuntan, and Yichang were found, and positive values in eigenvectors occurred at stations located in the lower reaches of the Changjiang basin (Fig. 11). Eigenvector changes at the six stations were in agreement with those from the second mode of streamflow decomposition in Fig. 4. This pattern suggests that the weak EASM and strong ENSO in the second mode may control streamflow changes in the Changjiang basin and cause low streamflow in the upper reaches and high streamflow in the lower reaches.

Although the eigenvectors for EASM and ENSO were higher than those in the third mode (Fig. 11A), there was no clear change in eigenvectors for streamflow at the six stations. Eigenweighting of this mode had also no obvious fluctuations, suggesting that this mode may be impacted by climate factors other than EASM and ENSO.

5. Conclusions

Precipitation and streamflow in Asia especially in the Changjiang basin is mainly influenced by EASM and ENSO. Intensive human activities also affect streamflow in the Changjiang catchments. The primary modes of streamflow changes in the Changjiang basin and associated factors were evaluated in this study. Conclusions can be drawn as follows.

1. Streamflow along the Changjiang can be divided into trend and periodic components. The former may be caused mainly by intensive anthropogenic activities in Changjiang catchments. In addition, rapid snowmelt induced by climate warming may cause additional water discharge into the upper reaches of the Changjiang. The periodic components may be induced by complicated synthetic climate factors.
2. The main mode of the periodic component of streamflow along the Changjiang is baseflow, which can remain relatively stable.

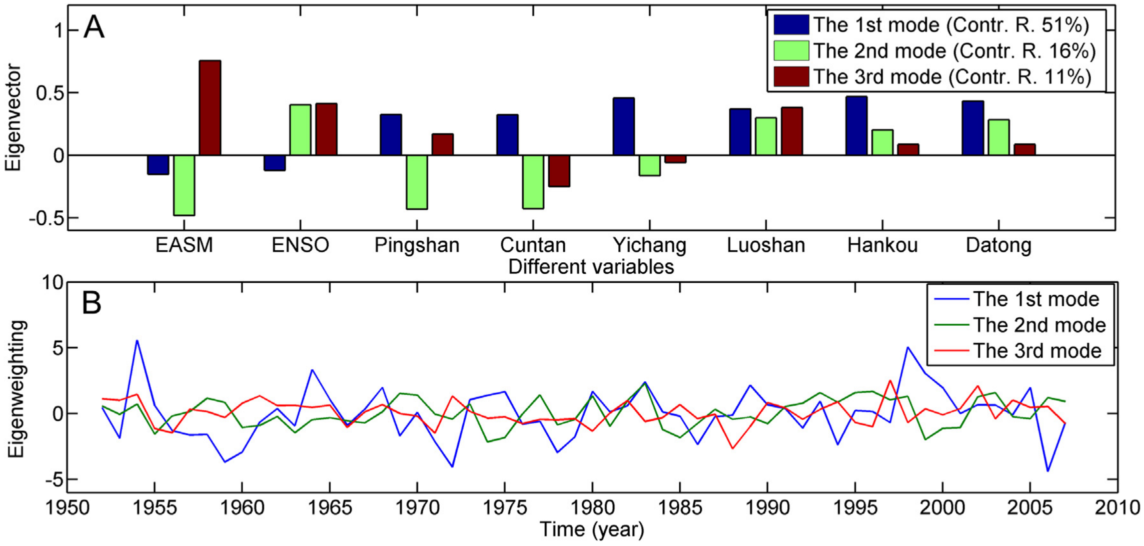

Fig. 11. Modes of coupling for both periodic components of streamflow changes and EASM and ENSO indices determined using EOF.

The baseflow had periodic oscillations, which were impacted by weak EASM and ENSO.

3. The second mode of the periodic component of streamflow along the Changjiang can be distinguished between the upper and lower reaches. There was an anti-phase relationship for streamflow in the upper and lower reaches. Variations in the second mode may be influenced by weak EASM and strong ENSO.
4. The EASM and ENSO impacted region in the Changjiang basin may be much larger in the lower reaches than in the upper reaches. Relatively weak EASM and La Niña events may induce increased streamflow. However, relatively strong EASM and El Niño events may cause decreased streamflow.

Acknowledgments

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