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Wavelet-based variability of Yellow River discharge at 500-, 100-, and 50-year timescales

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Water scarcity in the Yellow River, China, has become increasingly severe over the past half century. In this paper, wavelet transform analysis was used to detect the variability of natural, observed, and reconstructed streamflow in the Yellow River at 500-, 100-, and 50-year timescales. The periodicity of the streamflow series and the co-varying relationships between streamflow and atmospheric circulation indices/sunspot number were assessed by means of continuous wavelet transform (CWT) and wavelet transform coherence (WTC) analyses. The CWT results showed intermittent oscillations in streamflow with increasing periodicities of 1–6 years at all timescales. Significant multidecadal and century-scale periodicities were identified in the 500-year streamflow series. The WTC results showed intermittent interannual covariance of streamflow with atmospheric circulation indices and sunspots. At the 50-year timescale, there were significant decadal oscillations between streamflow and the Arctic Oscillation (AO) and the Pacific Decadal Oscillation (PDO), and bidecadal oscillations with the PDO. At the 100-year timescale, there were significant decadal oscillations between streamflow and Niño 3.4, the AO, and sunspots. At the 500-year timescale, streamflow in the middle reaches of the Yellow River showed prominent covariance with the AO with an approximately 32-year periodicity, and with sunspots with an approximately 80-year periodicity. Atmospheric circulation indices modulate streamflow by affecting temperature and precipitation. Sunspots impact streamflow variability by influencing atmospheric circulation, resulting in abundant precipitation. In general, for both the CWT and the WTC results, the periodicities were spatially continuous, with a few gradual changes from upstream to downstream resulting from the varied topography and runoff. At the temporal scale, the periodicities were generally continuous over short timescales and discontinuous over longer timescales.

1. Introduction

Water is essential for the survival of all organisms, including human beings (Oki and Kanae, 2006; Yang et al., 2017). Water availability is vital for human health, economic activity, ecosystem function, and geophysical processes (Milly et al., 2005). Nevertheless, during the past five decades, water scarcity has begun to accelerate across the world. It is estimated that by 2025 as many as 5 billion people – 60% of the 8 billion world population – will be living in countries suffering from water stress (Arnell, 1999). Therefore, the changing characteristics and optimal management of water resources have received great attention in recent decades.

From a resource perspective, runoff is an important component of the hydrological cycle and can be used as a measure of sustainable water availability (Milly et al., 2005; Yang et al., 2016). The temporal distribution of global runoff is extremely non-uniform, exacerbating the severe challenge posed by shrinking water resources. Substantial research effort has therefore been focused on streamflow and its fluctuations, including streamflow circulation, river flow oscillations, discharge predictions, etc. (Miao and Ni, 2009; Kong et al., 2015).

For a better understanding of fluctuations in streamflow, one can perform a decomposition of the runoff time series into time–frequency space to determine the dominant modes of variability and how such modes vary with time (Torrence and Compo, 1998). Time series in the geosciences generally show sporadic periodicities which are often caused by intermittent climatic oscillations. Most traditional mathematical methods that examine periodicities in the frequency domain, such as Fourier analysis, implicitly assume that the underlying processes are stationary in time (Grinsted et al., 2004), which is not the case in reality for most geo-scientific time series. Windowed Fourier transforms can be used but are limited by the arbitrary fixed length of the window (Torrence and Compo, 1998), and there is a tradeoff between temporal and spatial resolution because of Heisenberg's uncertainty principle. Wavelet analysis, however, has an advantage over the more classic techniques because it is not restricted by an assumption of stationarity

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(Cazelles et al., 2008). Wavelet analysis is a scale-independent, robust approach for decomposing time series into finer scales and is able to identify localized, scattered periodicities (Coulibaly and Burn, 2005).

Wavelet analysis has been widely applied in hydrology since the 1980s (Kumar and Foufoula-Georgiou, 1997). Labat et al. (2004) used a statistical wavelet-based method to reconstruct the monthly discharges of the world's largest rivers. They showed that there was a long dry period in global runoff between 1900 and 1940, followed by a succession of alternating 15-year-long dry and humid periods. This reconstruction displayed more pronounced amplitudes in the dry and humid periods compared with previous estimates. Labat (2008) further analyzed the changes in discharge of 55 large rivers globally using a Morlet continuous wavelet-based analysis, and demonstrated that large-river runoff exhibits El-Niño/Southern Oscillation (ENSO)-related and North Atlantic Oscillation (NAO)-related interannual variability, decadal variability, and multidecadal 40–50-year fluctuations. Smith et al. (1998) applied wavelet spectral analyses to the daily discharge records for 91 rivers in five different climate regions across the U.S., and found that the spectral curves were very similar within a region but differed between regions. Labat et al. (2000) applied the continuous Morlet wavelet transform and a multi-resolution orthogonal analysis to rainfall rates and runoffs for karst springs at two locations in France, with the data sampled at different rates. The results showed that both rainfall rate and karst spring runoff were characterized by highly non-stationary and scale-dependent behavior. Runoff was influenced by the large nonlinearities in the karstic system and by the time structure of the rainfall rates. Gaucherel (2002) exploited the benefits of the continuous wavelet transform (CWT) to detect new periodicities in the flow curves for basins in French Guiana. Their results showed that the so-called 'short March summer' (a temporary reduction in rain over the Guiana Shield during the rainy season) was due to the influence of the Atlantic Ocean on the continent. Nourani et al. (2013) used a wavelet transform to identify dynamic, multi-scale features in the runoff time series and to remove noise. The results showed that the application of the wavelet transform increased the performance of the feed-forward neural network (FFNN) rainfall–runoff models in predicting runoff peak values. Nalley et al. (2013) adopted the discrete wavelet transform (DWT) technique to detect trends in the mean surface air temperature over southern regions of Ontario and Quebec, Canada, for the period 1967–2006. They found that high-frequency components ranging from 2 to 12 months were more prominent in the higher resolution data. Pathak et al. (2016) used DWT to analyze variability in seasonal temperature, precipitation, and streamflow in the Midwestern United States. The results indicated an upward trend in temperature, with different periodicities being effective for detecting trends in different seasons and different hydrological components. Yarleque et al. (2016) adopted a high-resolution spatiotemporal wavelet reconstruction method to assess the spatial variability in precipitation over complex mountain terrain at multiple spatiotemporal scales; the validation study demonstrated the good overall performance of the wavelet method. CWT and wavelet transform coherence (WTC) analyses were applied by Niu and Chen (2016) to the hydrological time series (runoff, soil moisture, and evapotranspiration) for the ten sub-basins that make up the Pearl River basin in South China for the period 1952–2000. They found that runoff had greatest correlation with precipitation variability and least with evapotranspiration, and that the attenuation of runoff in response to precipitation variability occurred mainly within a timescale of two years.

One-dimensional CWT focuses only on a single variable (e.g. streamflow). Water discharge is an essential part of any sensible hydrological system, and is also strongly associated with internal climate feedback mechanisms (Miao et al., 2016), such as the known atmospheric circulation modes, and external forcings, such as solar activity (Hao et al., 2008). Knowledge of the spatially and temporally non-stationary behavior of streamflow is vital for a better understanding of the complicated hydrology–climate relationship and the dynamics of the hydrological cycle (Coulibaly and Burn, 2005), which in turn will assist with accurate prediction of water runoff.

To achieve this objective, two-dimensional wavelet transforms have been widely used [e.g. the cross wavelet transform (XWT) and wavelet transform coherence (WTC)]. The two-dimensional approach has the advantage of being able to detect transient associations between the studied non-stationary signals in both the time and frequency domains simultaneously (Yu et al., 2015). Calculated from two CWTs, the XWT exposes regions with high common power and further reveals information about the phase relationship. The WTC is also calculated from two CWTs and can quantify the degree of linear relationship between two series (e.g. precipitation and ENSO) in both the time and frequency domains. XWT reveals high common power; WTC finds locally phase-locked behavior.

Labat (2010) used XWT to study the relationship between annual continental freshwater discharge and five climate indices over the period 1876–1994. The study revealed temporal correlations between discharge and indices for five continents, sometimes over the entire time interval but more often over restricted intervals. Coulibaly and Burn (2005) used XWT to gain insights into the dynamic relationship between seasonal streamflow and the dominant modes of climate variability in the Northern Hemisphere: the wavelet cross-spectra revealed strong climate–streamflow covariance in the 2–6-year period after 1950, regardless of climatic index or season. Briciu and Mihăilă (2014) used WTC to study the influence of climatic oscillations and sunspot number on river flows in Romania, Ukraine, and Moldova. The WTC analysis showed that there was an approximately 11-year periodicity between sunspots and river flow, which indicates the constant influence of solar activity on climatic oscillations and rivers. Gobena and Gan (2009) used WTC to identify links between primary Pacific climate variability modes and low-frequency hydroclimatic variability in the South Saskatchewan River basin in Canada. At the interannual scale, Gobena and Gan observed strong coherency but inconsistent phase differences between streamflow and the Niño 3 index, the Pacific–North America pattern (PNA), and the Pacific Decadal Oscillation (PDO). At the interdecadal scale, the PDO and streamflow exhibited consistently strong coherence with a stable phase difference of 180° at scales >20 years. Nalley et al. (2016) applied WTC to analyze the relationships between streamflow data collected from the southern regions of Quebec and Ontario over 55 years and the ENSO, the PDO, and the Arctic Oscillation (AO). WTC analyses showed that the inter-annual influence of the ENSO and the NAO occurred at 2–6 year periodicities, and that the influence of the PDO occurred at periodicities up to 8 years and exceeding 16 years. Keener et al. (2010) used both XWT and WTC to identify and quantify the significance of a teleconnection between sea surface temperatures (SST) associated with the Niño 3.4 index and streamflow in the Little River watershed in Georgia, USA. The strongest 3–7 year shared power was observed between SST and streamflow data, whereas the strongest co-variance was observed between SST and NO_3 load data. Wang et al. (2013) used XWT and WTC to assess the possible relationships between monthly extreme headwater flow in the Tarim River basin, climatic indices, and regional climate. The results showed that different circulation indices may influence the trends in hydrological extremes in different rivers. Tamaddun et al. (2016) used XWT and WTC to analyze the interaction between streamflow in the western United States and climate indices over the period 1951–2010. The results showed that changes in streamflows were coincident with both the ENSO and the PDO, but in different time-scale bands and at various time intervals. The ENSO was strongly correlated with streamflow in the 10–12 years band whereas the PDO was strongly correlated with streamflow in the 8–10 years and >16 years bands.

The Yellow River (or Huanghe) is the sixth longest river in the world (Yellow River Conservancy Commission (YRCC), 2012). Northern China has heavy socio-economic dependence on the Yellow River, with about 110 million inhabitants occupying its basin in 2000 (Miao and Ni, 2009). For the past half century, the Yellow River has been suffering from water