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Multi-scale streamflow variability responses to precipitation over the headwater catchments in southern China

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ABSTRACT

This paper examines the multi-scale streamflow variability responses to precipitation over 16 headwater catchments in the Pearl River basin, South China. The long-term daily streamflow data (1952–2000), obtained using a macro-scale hydrological model, the Variable Infiltration Capacity (VIC) model, and a routing scheme, are studied. Temporal features of streamflow variability at 10 different timescales, ranging from 6 days to 8.4 years, are revealed with the Haar wavelet transform. The principal component analysis (PCA) is performed to categorize the headwater catchments with the coherent modes of multi-scale wavelet spectra. The results indicate that three distinct modes, with different variability distributions at small timescales and seasonal scales, can explain 95% of the streamflow variability. A large majority of the catchments (i.e. 12 out of 16) exhibit consistent mode feature on multi-scale variability throughout three sub-periods (1952–1968, 1969–1984, and 1985–2000). The multi-scale streamflow variability responses to precipitation are identified to be associated with the regional flood and drought tendency over the headwater catchments in southern China.

1. Introduction

Streamflow responses to precipitation variability varies at different scales (Rathinasamy et al., 2013, 2014), with the effect to either amplify or attenuate the precipitation's variability modes (Shun and Duffy, 1999; Markovic and Koch, 2015). These responses are incorporated results of interactions between climate and land surface factors, such as interception and evapotranspiration, runoff generation and routing, and snow melting, which make the output signal (streamflow) to diversify the spectral characteristics to the input signal (precipitation) (Labat, 2006, 2010). The responses alternate the homogeneous coherent hydrological regions from precipitation to streamflow. Knowledge of how these responses change the coherent modes of different hydrological variables is helpful to identify dominant control mechanisms on the terrestrial hydrological cycles (Saco and Kumar, 2000; Sivakumar, 2004).

A major challenge in delineating the coherent regions of hydrological responses is the difficulty in obtaining streamflow record (as the representative) of the basin/sub-basin area, which may come from several situations: (1) there is no outflow record for the basin or the record is not long enough; (2) streamflow stations are not close to the basin outlet; and (3) only the outflow record at the basin boundary has to represent the features of the entire large-scale basin. To identify coherent regions over the United States, Guetter et al. (1994) used the streamflow data for the period 1939–1988 along the geographical border of the United States and aggregated these data within basin segments of 3° latitude along both the east and west coasts and 3° longitude along the Canadian border, Great Lakes, Mexican border, and the Gulf States. Over the conterminous United States, they identified 10 homogeneous regions of monthly flow anomalies. Saco and Kumar (2000) used these data further to explore the coherent modes in multi-scale variability of streamflow. In these studies, the entire Mississippi River basin was characterized as a single mode with the drainage area of over 3.19 million km^2 and one outflow station S09 (Guetter and Georgakakos, 1993), when the delineation of coherent region was based on streamflow observations.

An alternative way to obtain the streamflow data of the basin or sub-basin outlets is the utilization of the simulation results of a

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hydrological model. To this end, over the past two decades, a number of Macroscale Hydrological Models (MHMs) have been developed to model the land surface hydrological dynamics of large continental river basins (Abdulla et al., 1996; Kuhl and Miller, 1992; Nijssen et al., 2001a). The advancement of the sub-grid variability descriptions associated with soil, terrain and vegetation heterogeneities motivated the development of more complex MHMs (Liang et al., 1994; Lakshmi, 2000; Chen and Kumar, 2001). Among these MHMs, the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) is a physically-based and semi-distributed model and maintains both surface energy and water balances over grid-cell basis. The VIC model has been widely applied for analyzing terrestrial hydrological processes. For instance, Nijssen et al. (2001a) used the VIC model to predict discharges for 26 global rivers, including the Amazon, Danube, Mekong, Mississippi, Brahmaputra, Lena, and the Olenek River. Maurer et al. (2002) provided a long-term (1950–2000) hydrological dataset of land surface fluxes and states, including evapotranspiration, runoff, soil moisture, snow water equivalent, and energy fluxes, for the conterminous United States. As the runoff generation output is computed for each grid cell, it can be easily tailored to represent the basin outflow response for the different sub-regions within the studied area. Lakshmi et al. (2004) used the VIC-simulated hydrological data to investigate the floods and droughts in the Upper Mississippi basin and identified a strong relationship between droughts and the third layer soil moisture variability. The advantage of the VIC model, and other MHMs, allows us to study the coherent regions with the hydrological time series of a desirable sub-basin area.

Apart from the physically-based modelling, stochastic time series analysis is a useful tool to summarize the spectral changes of precipitation through the various stages of the hydrological cycle. For example, Syed et al. (2004), in examining the process controls in land surface hydrological cycle, performed the principal component analysis (PCA) on assimilation data to ascertain the contribution of physical variables to the hydrological processes over the conterminous United States. Niu et al. (2016) examined the coherent modes of precipitation in the Pearl River basin based on daily time series by using Haar wavelet transform and PCA. Such an approach can account for the differences in temporal scale of fluctuations embedded in the time series (Smith et al., 1998; Saco and Kumar, 2000) and grasp basin clusters that exhibit similar distribution of variability across a number of timescales. In the study of Niu et al. (2016), the 16 headwater catchments were selected to consider non-nested river network and different levels of catchment size. Two coherent modes, with the high small scale (3 days–2 weeks) and high seasonal scale (about 6 months) variability power, were found to be able to explain over 90% of the precipitation variability over the 16 headwater catchments.

Following up on the study by Niu et al. (2016), this study focuses on the coherent region delineation of streamflow variability in the Pearl River basin in South China. The VIC model and a routing scheme are employed to simulate the streamflow series for 16 selected headwater catchments in the basin (see Fig. 1) over the period 1952–2000. The focus in this study is on the natural streamflow variability, since anthropogenic effects are not considered by the simulated hydrological processes for the large-scale basin. The rest of the paper is organized as follows. Section 2 introduces the study area, the Pearl River basin. Section 3 presents the models and methods for streamflow simulation and analysis, including the VIC model, routing scheme, Haar wavelet transform, and principal component analysis. The corresponding model input and validation data are also described in this section. Section 4 presents the VIC model simulation results, describes the wavelet analysis of streamflow, performs the analysis for both observed and simulated streamflow at the gauging stations, and details the application of PCA for identifying regional coherent regions. Section 5 discusses the results from these analysis, and Section 6 draws some conclusions.

2. Study area

The total area of the Pearl River basin is about 450,000 km^2, with the river length 2214 km (Fig. 1). The basin is within a tropical and subtropical monsoon climate region. The long-term average annual precipitation in the basin is 1477 mm, and annual water resources is about 337 billion m^3 (Pearl River Water Resources Commission, 2005). For the period 1951–2000, the runoff in the wet season (April to September) was about 80% of the total annual runoff, and the ratio of runoff amount between the wettest year and the driest year can reach 6–7 (Niu and Chen, 2009). Due to

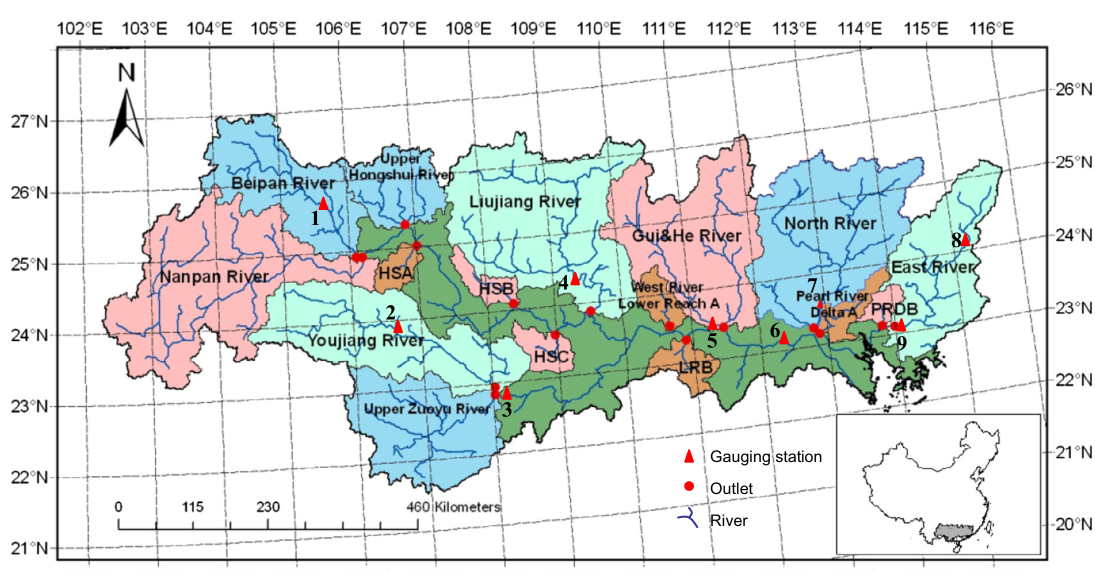

Fig. 1. The 16 headwater catchments (with the name marked) and corresponding outlets in the Pearl River basin in South China. The gauging stations are: 1. Zhedong; 2. Baise; 3. Nanning; 4. Liuzhou; 5. Wuzhou; 6. Gaoyao; 7. Shijiao; 8. Longchuan; 9. Boluo.