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YANGTZE DISCHARGE MEMORY *

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Abstract　We present a review on studies focusing on memories in hydrological time series in the Yangtze Basin based on observational and reconstructed historical data. Memory appears as scaling of power spectra, $S(f) \sim f^{-\beta}$, with $0 < \beta \leqslant 1$. The presence of scaling is noteworthy in daily river discharge time series: 1) from weeks to a couple of years, power spectra follow flicker noise, that is $\beta \approx 1$; 2) beyond years, spectral scaling approaches $\beta \approx 0.3$. In historical time series of floods and droughts, power spectra also shows scaling with $\beta \approx 0.38 \sim 0.52$. Furthermore, a 70-year peak is detected in historical maritime events series, which also appears in other past climate indicators. Presence of memory in these hydrological time series implies clustering of extremes and scaling of their recurrence times, therefore, probabilistic forecast potential for extremes can be derived. On the other hand, although several physical processes, for example, soil moisture storage and high intermittency of precipitation, have been suggested to be the possible candidates contributing to the presence of long term memory, they remain open for future research.

Key words　Yangtze, hydrological memory, past climate
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1 Introduction

Memory in the climate system implies predictive potential of the future, without which daily weather forecasts, for example, would not be possible. It can be measured by the time integral of the auto-correlation function of a time series. In this manner short term memory can be distinguished from long term memory (LTM): the former is characterized by a finite integral time scale, which indicates a limit of deterministic predictability; the latter, however, is linked to an infinitely large integral time scale. LTM has important implications: (i) extreme events show long-term interdependence, contrasting the conventional assumption of their independence, and (ii) there is (probabilistic) predictability in their recurrence times, because their frequency distribution also follows a power law scaling[1,2]. In this sense, searching for scaling properties in the climate system is not merely an academic exercise, but useful for prediction[3,4] or, at least, a forecast potential may be inferred.

In the subsequent sections we corroborate analyses of scaling properties of time series related to the water flow of the Yangtze and some related climate events[5,6]. Due to inherent complexity and the close relevance for humans and their environment under climate-change and man-made stress, the Yangtze provides a challenging test-bed for applying non-linear systems analysis methods. This article is arranged as follows: after introducing the data sets and analysis methods (section 2), results from previous studies are presented in a comprehensive view (section 3): first, the evaluation of discharge time series is presented identifying scaling properties from weeks to years; second, related historical climate indicators are analyzed using detrended fluctuation analysis (DFA) and power spectra, to estimate scaling and periodicities for time scales up to centuries. Summary and outlook are presented in section 4.

2 Yangtze Basin: Data and methods of analysis

The Yangtze is the longest river in China and the third longest in the world. It originates in the Qinghai-Tibet Plateau and flows about 6300km eastwards to the East China Sea (Fig. 1) with a drainage basin of about $1.8 \times 10^6 km^2$. Situated between 91°E to 122°E and 25°N to 35°N in East Asia, it is embedded in a complex topography and exposed to subtropical monsoons.

2.1 Data

Daily discharge data are available for over decades at several stations in the upper and lower reaches of the Yangtze River basin (Fig. 1): 1) Cuntan (29°37′N, 106°36′E; altitude 164.68m), data from 1892 ~

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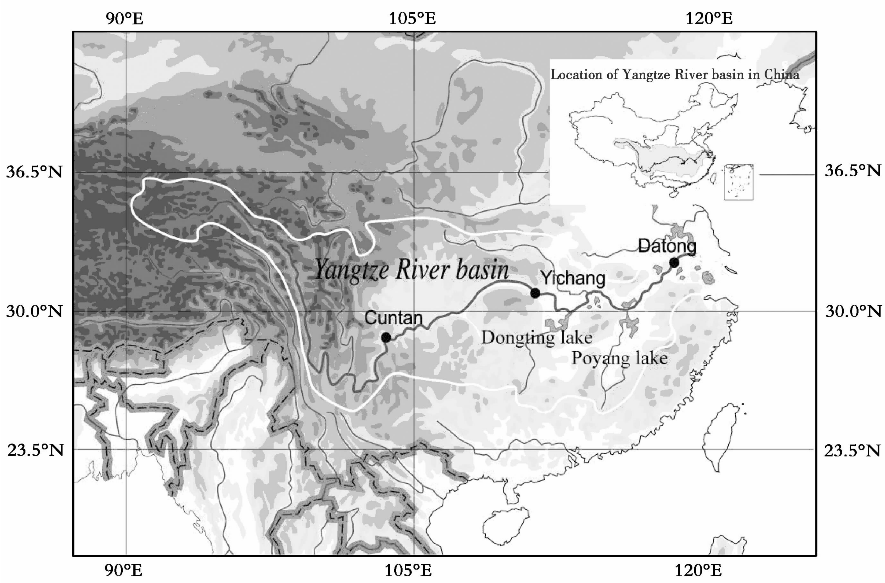

Fig. 1 Yangtze River basin with stations Cuntan, Yichang, Datong, and lakes Dongting and Poyang[6]

2004; 2) Yichang (30°40′N, 111°14′E; altitude 44.10m), from 1946 ~ 2004; and 3) Datong (30°46′N, 117°37′E; altitude 8.75m), from 1950 ~ 2000. The common period 1950 ~ 2000 is analyzed. Cuntan is located in the mountainous area of the Yangtze Basin with an upstream contributing drainage area of $0.6 \times 10^6 km^2$. At Yichang near the Three Gorges the Yangtze accumulates the runoff from the upper mountainous area to the middle plain. Datong near the estuary characterizes the contributions from the upstream area; it is assumed as the tidal limit of the East China Sea, thus tides have only marginal effects there and, if any, only in winter. The dataset is provided by Changjiang Water Resources Committee[5].

To characterize Yangtze climate variability on the time scale beyond decades, results based on historic records of indicators of floods and droughts and maritime events are presented. From historic documents, floods and droughts are quantitatively extracted for period from year 1000 to 1950: first, a grade is assigned to each year to characterize individual heavy flood, flood, normal, drought, and heavy drought events. Second, the number of droughts and floods is summed up at 10-year intervals forming a decadal indicator of floods and droughts, which is complemented by instrumental observations from 1950 to 2000. The number of maritime events per decade is constructed in a similar manner but covers the period from 1000 to 1950. Details of the data origin are given in Jiang *et al.*[5].

2.2 Methods

Power spectrum analysis and DFA are applied to the data set, after the annual cycle based on calendar days have been subtracted from the original data (the log-transformed discharge annual cycle and spectra do not differ). Details are given as follows:

(1) Power spectra $S(f)$ are determined using Matlab spectrum periodogram routine. The exponent β in the power law, $S(f) \sim f^{-\beta}$, is determined by a least-square fit in a log-log plot of the power spectrum.

(2) DFA also determines variability of time series on different time scales[7], which is well suited to derive LTM[8]. It is based on the fluctuation function $F(t)$ for the integrated time anomaly time series, the so-called profile. Linear fits (DFA-1) or higher order N polynomials (DFA-N) are determined for segments of varying width t. The fluctuations $F(t)$ are the means of the variances of the profile with respect to the fits. DFA-N time scales of interest are (about 5 to 10 times) shorter than the lengths of the time series since conditions for significance apply.

(3) LTM shows up as a power law in both DFA analysis and power spectrum, both of which are directly related to the correlation function: if the fluctuation function scales as $F(t) \sim t^{\alpha}$, the power spectrum of the same time series follows $S(f) \sim f^{-\beta}$ with $\beta = 2\alpha - 1$, and the correlation function is $C(t) \sim t^{-\gamma}$ with $\gamma = 1 - \beta$. Furthermore, the fluctuation exponent α equals the Hurst exponent obtained by the rescaled range. Stationary LTM is present within $0 < \beta < 1 (0.5 < \alpha < 1.0)$.

The two limiting cases are uncorrelated time series (white noise) with $\beta = 0$ ($\alpha = 0.5$) and the $1/f$-spectrum (flicker noise) with $\beta = 1$ ($\alpha = 1$). For $\beta > 1$ ($\alpha > 1$) the time series is non-stationary and conventional statistical analysis cannot be applied. In the case of dominant oscillations the fluctuation function $F(t)$ shows step-like transitions at the oscillation periods, and hence, the result may be difficult to interpret for a multitude of oscillations.

3 Fluctuations in the last millennium

The scaling analysis is applied to interpret the hydrological variability in the Yangtze Basin on time scales up to centuries. Power spectrum and DFA are applied to demonstrate properties of both scaling and periodicity, and implications are noted. More details are found in the references.

From days to years (Fig. 2): The intra-annual variability of the daily Yangtze discharge (Fig. 2a) is analyzed at station Cuntan and Yichang located in the upper reaches, and Datong in the lower reach. A direct view of the time series (Fig. 2a) reveals the discharge to be dominated by summer (July to September) monsoon rains. The coherence between Cuntan and Yichang shows a one-day lag, while Datong appears to be smoothened. The power spectrum is shown only for station Yichang (Fig. 2b): 1) for time scales ranging from about 2 weeks to several years, the spectrum $S(f) \sim 1/f$ (or flicker noise) is observed; 2) on larger time scales (beyond several years) spectral scaling approaches $\beta \approx 0.3$, which indicates a weak stationary LTM; and 3) on shorter time scales (below two weeks), the scaling is rather steep $\beta \approx 3.5$. The spectrum at station Cuntan (not shown) is similar to that at Yichang. At Datong, which is located in the lower reach of the Yangtze (not shown), flicker noise commences at about 2 months and, on shorter time scales, the scaling is flatter ($\beta \approx 0.7$ below one week). The regime difference between the upper and lower reaches of the Yangtze is contributed by the extended lake systems, which functions as a low pass filter with a decay time of about one week so that the flow at Datong responds to the input from Yichang within a time scale of one week[6].

Causes and implications: $1/f$-scaling of the intra-annual variability spectra in Yichang (and Cuntan) shows discharge as a non-stationary and intermittent process with extreme variability and highly fluctuating wet season means (Fig. 2a). The $1/f$-variability in the upper reaches cannot be related directly to regional precipitation, because the spectrum of precipitation is white beyond one week[6]. Therefore, further processes acting on a broad spectrum of time scales in the upper reaches, including the local soil storage properties and the high intermittency of precipitation, need to be considered in future research. It has been explored that pulse-like events as the highly intermittent precipitation may form $1/f$ scaling[9,10]. In addition, groundwater stream-flow can also introduce memory with widely distributed monthly time scales[11]. The spectral variability of river discharges shows very different short and long-term characteristics. This distinct non-universal behavior is not understood but may be attributed to catchment topography and groundwater flow since precipitation is found to be uncorrelated (spectrally white) world-wide.

From years to centuries: Decadal time series of flood and drought occurrence in the Yangtze Delta for the period between year 1000 and 2000 are presented in Fig. 3a. This time series is subjected to DFA to determine the LTM. For the duration of 1000 years, results in the time range up to centuries can be reliably derived. The fluctuation functions follow straight lines with $\alpha > 0.5$ ($\beta > 0$) representing LTM up to different time scales (Fig. 3b): 200 years for floods and without restriction for droughts. The Hurst exponents are $\alpha \approx 0.69$, corresponding to $\beta \approx 0.38$ for droughts and $\alpha \approx 0.76$ ($\beta \approx 0.52$) for flood frequencies. Higher order

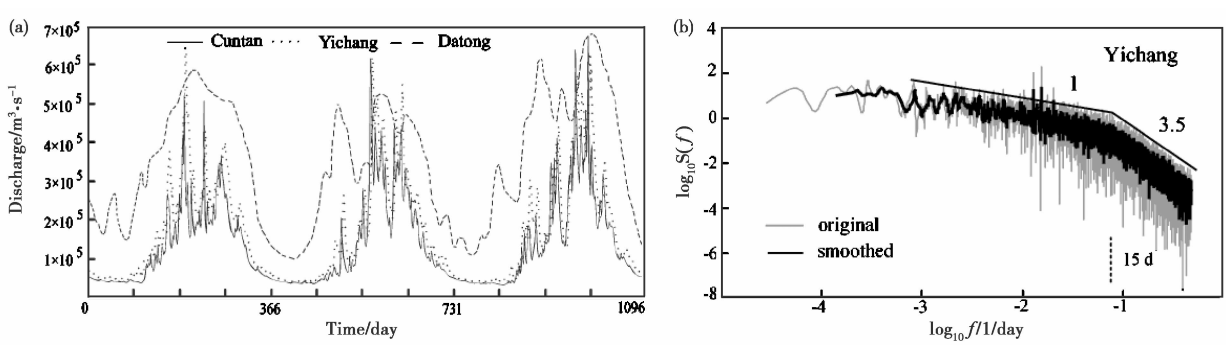

Fig. 2 Daily discharge of the Yangtze

(a) time series at station Cuntan, Yichang, and Datong from 1950 to 1952, (b) power spectrum of the river discharge at Yichang from 1950 ~ 2000 (Slopes indicate power-laws, $S(f) \sim f^{-\beta}$, with exponents obtained by rounded fits

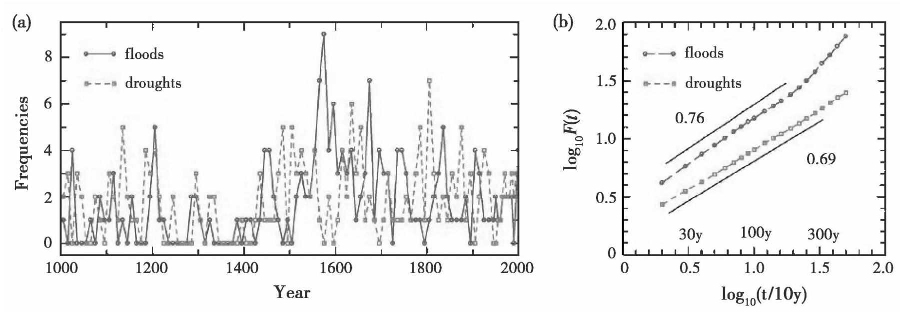

Fig. 3 Floods and droughts in the Yangtze Delta from 1000 ~ 2000
(a) frequency in number of events per decade, and (b) fluctuation functions obtained using DFA-1; slopes indicate LTM power-law exponents α in the fluctuation function (taken from Fraedrich *et al.*[2])

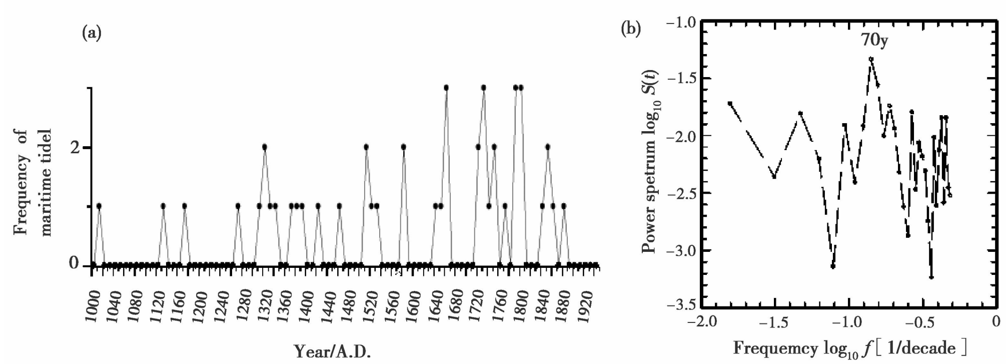

Fig. 4 Maritime events from 1000 ~ 1950
(a) frequency, and (b) power spectrum averaged over three non-overlapping time segments

DFA-2 and DFA-3, which characterize the role of linear and quadratic trends on time scales below 100 years, reveal the same scaling (power laws) as DFA-1.

A 70-to-100 year period (Fig. 4): The frequency of maritime events, however, shows a somewhat different pattern of low frequency variability, namely, periodicity (Fig. 4a and 4b). Power spectral analysis (Fig. 4b, determined as an average of three disjoint time segments) yields an oscillation with a period around 70 years, and long time correlations with scaling appear to be absent. As this periodicity has been reported in other historical time series in China[12], search for its origin is relevant, in particular, if climate prediction is on the agenda. Though coupled global ocean-atmosphere modes of multidecadal variability[13] are suggestive, more research is required, in particular on the impacts on regional climate and water cycle.

4 A brief summary and outlook

This review presents results on Yangtze River discharge varying from days to centuries; it is embedded in past and ongoing research on low-frequency variability in the hydrological cycle, its causes and its predictability of the Yangtze River system and of the climate of China. This article focuses on scaling properties, which characterize long term memory (LTM) without preferred periodicities but scale interrelations.

Presence of LTM has important implications for future research: 1) it is responsible for clustering of extreme events and scaling of their recurrence time which, in turn, allows for probabilistic extreme event prediction[1,2]: the presence of LTM in time series leads to long return times of extreme events: for uncorrelated data (without memory) the return times T are exponentially distributed; for weak LTM, however, the exponential distribution is systematically modified by stretching, $T^{1-\beta}$. 2) Another aspect of future research lies in the possible source of LTM occurring in the hydrological cycle of the Yangtze. Sources may be fluctuations in the Pacific and Atlantic Ocean[13]. For example, atmospheric bridging across Eurasia, which has been demonstrated to affect the water cycle extremes in the Tibet Plateau in the summer months[14], could provide the missing link for understanding the scaling behaviour on shorter (up to decades) and longer (up to centuries) time scales. In this sense, Yangtze and Nile[15~17] are close relatives; they share similar fates in their relation to humans and also research wise, because the scaling analysis demonstrated here, has (possibly first) been applied to the Nile[18,19]. This also holds for the embedding of Yangtze and Nile in the large scale climate dynamics.

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