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Yangtze 1/*f* discharge variability and the interacting river—lake system

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Summary The intra-annual variability of the daily Yangtze discharge is analysed at the stations Cuntan and Yichang located in the upper reaches, and at Datong in the lower reach. The intra-annual power spectra at Cuntan and Yichang follow $S(f) \sim 1/f$ within time scales from one week to one year. Since precipitation in this region follows a white spectrum (S = const), the origin of $1/f$-noise is possibly related to a broad distribution of time scales in the subsurface flow. The non-stationarity related to the $1/f$-spectra complicates the application of statistical forecast methods. The spectrum at Datong is considerably steeper, $f^{-3.5}$ up to two months. This variability is explained by storage and delayed release in the extended lake system connected to the Yangtze. A simple low pass filter suggests that the flow at this station responds to the input in Yichang with a time scale of eight days.

Introduction

Disastrous floods in the Yangtze Delta claimed up to a million lives during the last centuries. Trends and long-term variability of floods and droughts in the Yangtze delta are documented for the last millennium (Jiang et al., 2005). From the steep mountainous upper reaches the Yangtze passes to the middle and the lower meandering reaches where it interacts with extended lake systems and numerous tributaries contributing 50% of the total flow (Chen et al., 2001). During the last 50 years the construction and strengthening of dams along the upper reaches and levees in the lower reaches could reduce the impact of floods. Nevertheless the variability of the Yangtze on short and long time scales is still of major interest for agriculture and settlement, and remains a challenge for flood protection and forecast (for example the Yangtze River Flood Control and Management Project, YRFCMP).

On inter-annual time scales the Yangtze discharge (at the station Hankou/Wuhan, between Yichang and Datong) reveals long-term memory (LTM, equivalent to enhanced

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low frequency variability) with a scaling power spectrum of $S(f) \sim f^{-\beta}$ and $\beta \approx 0.3$ (Blender and Fraedrich, 2006), which has been reproduced by a high resolution ($2° \times 2°$) coupled atmosphere—ocean circulation model (ECHAM5/MPI-OM) showing precipitation without auto-correlation in the Yangtze catchment. LTM was discovered for the river Nile (Hurst, 1951), later for French catchments with $\beta = 0.7$ (Tessier et al., 1996) and, for a worldwide river data set, with $\beta = 0.5$ (Pelletier and Turcotte, 1997). LTM and extreme event characteristics of river flows have been interpreted as Joseph and Noah effects, and modeled in terms of self-similar processes by Mandelbrot and Wallis (1968). Granger (1980) has shown that the sum of independent AR(1) processes with distributions of regression coefficients can show scaling power spectra and long-term memory. This has been applied to river networks by Mudelsee (2007). LTM is a distinct property of the climate system with $1/f$-noise over parts of the ocean and white noise over the inner continents (Fraedrich and Blender, 2003).

For time scales between weeks and several years, Pandey et al. (1998) observe $\beta = 0.72$ and Dahlstedt and Jensen (2003) $\beta = 1$ for three rivers (Danube, Mississippi, and Wye/England). A similar result is found by Livina et al. (2007) for three Bavarian rivers. Kantelhardt et al. (2006) and Koscielny-Bunde et al. (2006) find a broad distribution of $\beta = 0...1$ in more than 40 rivers worldwide in this frequency range. In daily data river flow variability has been analysed by the chloride concentration at Plynlimon (Wales) by Kirchner et al. (2000), who find $1/f$-scaling ($\beta = 1$) over three orders of magnitude ranging from weeks to several years. As far as we are aware, the intra-annual variability of the Yangtze discharge has not been analysed up to now.

The results described above reveal that river discharges show power spectral scaling on many time scales between several days and decades. Since the observed spectrum of precipitation is nearly white (with exponents in the range $\beta = 0...0.2$), precipitation can be excluded as the origin for the scaling behavior of the river flows. Based on 13 daily European precipitation time series Fraedrich and Larnder (1993) suggest an intra-annual spectral plateau. This white spectrum is also found by Kantelhardt et al. (2006) in long daily precipitation records from 99 meteorological stations representative for different climate zones.

Thus, the non-universality of the river flow spectra can be related to the different local soil storage properties and the high intermittency of precipitation. In general, these spectra, which reveal the absence of characteristic time scales, are related to complex nonlinear interactions. However, for spectral power-laws with integer and half-integer exponents, the variability can be explained by linear diffusion processes (Fraedrich et al., 2004).

The aim of this paper is a spectral analysis of the daily discharge of the Yangtze from the upper to the lower reaches in Cuntan, Yichang and Datong on intra-annual time scales. The spectral variability along the Yangtze is used to interpret the impact of the extended lake system connected to the Yangtze in terms of a simple filter model. In Section ''Geographical setting, data, and methods'' the geographical setting, the datasets and the methods are described. In Section ''Intra-annual discharge variability'' the spectra along the Yangtze are compared and, in Section ''Impact of lake reservoirs'', a simple model for the lake induced filter at Datong is derived. Section ''Summary and conclusions'' concludes with a summary and conclusions.

Geographical setting, data, and methods

The Yangtze, being the longest river in China and the third longest river in the world, originates in the Qinghai-Tibet Plateau and flows about 6300 km eastwards to the East China Sea (Fig. 1). The Yangtze basin lies between 91—122°E and 25—35°N, and has a drainage area of 1.8×10^6 km^2, with mean annual discharge of 23,400 m^3/s on the middle river (monitored at Hankou station). The Yangtze is a major source of surface water for China, accounting for 38% of all surface water discharges in China. Located in the East Asia subtropical zone, the Yangtze River basin is climatically characterized by a subtropical monsoon climate with a mean annual precipitation of 1090 mm. In the past decades, the Yangtze River basin has suffered disastrous flooding events due to heavy monsoon rainfalls (see, for example Su et al., 2006).

The summer monsoons account for 40% of the total discharge, while winter discharge is mainly due to snow melt (Jiang et al., 2007). The lag between precipitation and discharge is estimated as one month which is affected by human activities (Yin and Li, 2001; Wang, 2005). As a result of the complicated topographic variation and climate conditions, the soil types of Yangtze river basin have a broad distribution, including paddy soil, dark semi-hydromorphic soils, red soil, yellow soil, yellow—brown soil, purple soil, skeletal primitive soils, mid-high mountain soil, and Alpine soil. The station Datong is generally considered the tidal limit of the East China Sea and tides have only marginal effects here, at the most in winter.

The dataset analysed is provided by the Changjiang Water Resources Committee (CWRC) and consists of daily records at the three hydrological stations, Cuntan (106°36′E, 29°37′N, 165 m a.s.l., 1892—2004), Yichang (111°14′E, 30°40′N, 44 m, 1946—2004), and Datong (117°37′E, 30°46′N, 9 m, 1950—2000) from the upper to the lower reaches of the Yangtze River basin. To obtain an optimal overlap, the period 1950—2000 is chosen for this study. The Yangtze discharge shows no distinct trend during the last century at the stations Yichang and Hankou (Chen et al., 2001), although the contribution of the melting of glacier has presumably increased.

Cuntan is located in the mountainous area of the Yangtze basin with an upstream contributing area of 0.6×10^6 km^2. At Yichang near the Three Gorges the Yangtze accumulates the runoff from the upper mountainous area to the middle plain, covering an area of 10^6 km^2. Datong is located near the estuary and measures the contribution in an upstream area of 1.7×10^6 km^2. There are three major tributaries between the stations Yichang and Datong: the outflows of the lakes Dating and Poyang (areas 3×10^5 km^2 and 1.6×10^5 km^2), and the Huanjing River (1750 km with a catchment of 1.59×10^5 km^2) flowing into the Yangtze between the Dongting and Poyang lakes. Human activity has modified the Yangtze basin by building dikes, canals, electric pumps, and small reservoirs. Here we concentrate on the effect of the two big lakes Dongting and Poyang, which exchange water with the Yangtze.

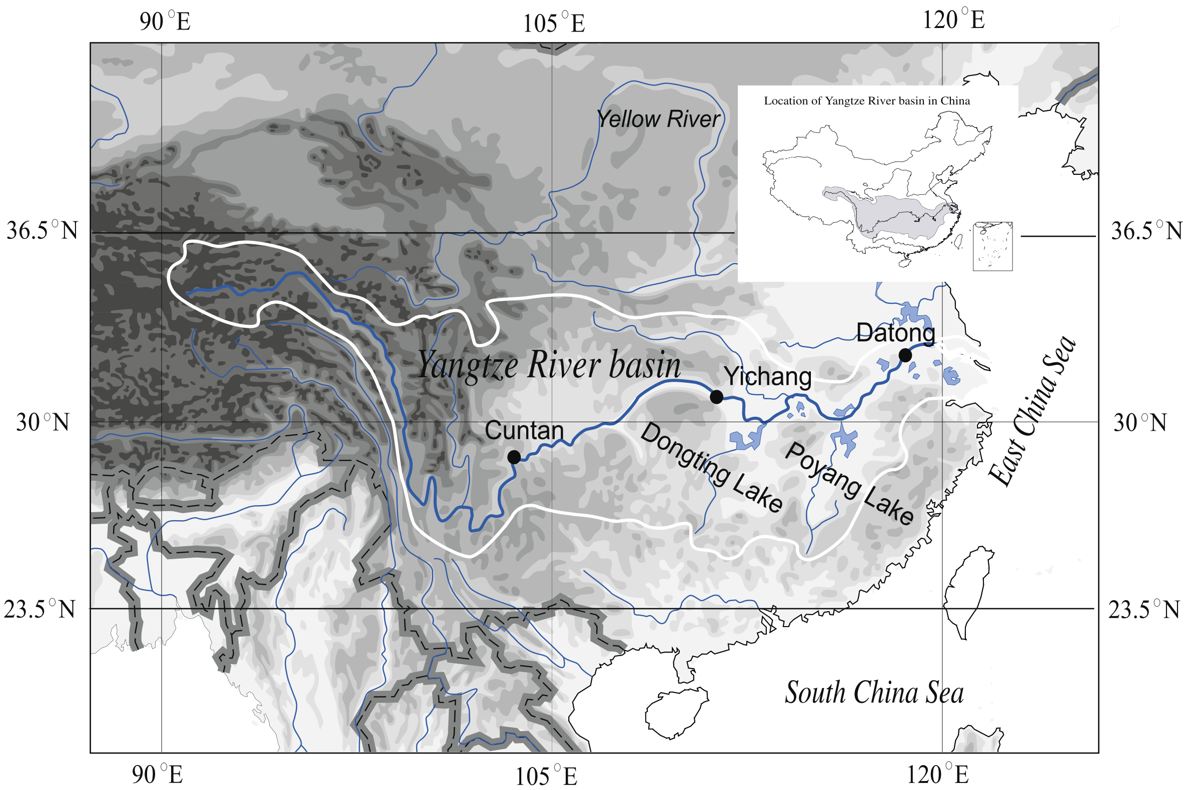

Figure 1 Yangtze basin with the stations Cuntan, Yichang, Datong and the lakes Dongting and Poyang.

Temporal variability of the discharge time series is subjected to power spectrum analysis. The power spectra $S(f)$ are determined by the Matlab periodogram routine spectrum.periodogram. 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.

Intra-annual discharge variability

The discharge along the Yangtze is analysed at the stations Cuntan, Yichang, and Datong (see Fig. 1). As an example, the first three years of the data (1950–1952, Fig. 2) reveal common properties and major differences between the stations: (i) The summer season dominates the discharge. (ii) The stations Cuntan and Yichang are coherent with a time lag of approximately one day. (iii) Datong appears as a smoothed version of the upstream flow. The analysis below has been performed with the original as well as the log-transformed discharge data. Since the main results for the annual cycle and the spectra do not differ we present the results for the original discharge data. The distribution of the discharge data is analysed after subtraction of the annual cycle.

The annual cycle of the discharge at Yichang, computed as the average flow for each day-of-the-year, and the frequency distribution of the anomalies (annual cycle subtracted from the observed flow) are shown in Fig. 3a and b. The annual cycle is dominated by the monsoon during July–September; due to the high intra-annual variability the average still fluctuates considerably although it is obtained for 51 years. The analysis below shows that this is due to non-stationarity for time scales up to one year. The anomaly distribution in Fig. 3b is clearly non-Gaussian with a tendency towards an exponential decrease for positive deviations.

The power spectra for the three stations (Fig. 4) reveal a slope $\beta = 1$ in Cuntan and Yichang for time scales >15 days; in Datong this $1/f$-spectrum appears >50 days (the slopes are rounded fits). For time scales <15 days (<50 days in Datong) the spectrum is steep following $\beta = 3.5$; downstream at Datong the spectrum becomes comparably flat for time scales below one week (indicated by $\beta = 0.7$). For larger time scales the spectra approach scaling with $\beta = 0.3$ (Blender and Fraedrich, 2006) representing weak stationary long-term memory.

The $1/f$-scaling of the intra-annual variability spectra in Cuntan and Yichang means that discharge appears non-stationary on time scales below one year. This fact is visualized by the intermittent structure and the extreme variability in Fig. 2 (a general relationship between $1/f$-spectra and extreme value statistics has been found by Antal et al. (2001)). The non-stationarity of the $1/f$-variability is the reason for the fluctuations of the wet period averages in Fig. 3a.

To determine the origin of these discharge spectra, precipitation is averaged over 68 stations in the upper reaches of the Yangtze catchment. Fig. 5 shows that the power spectrum of the mean precipitation is clearly white beyond one week, in agreement with all previous analyses (Kantelhardt et al., 2006). Hence precipitation cannot be the source of the discharge variability.

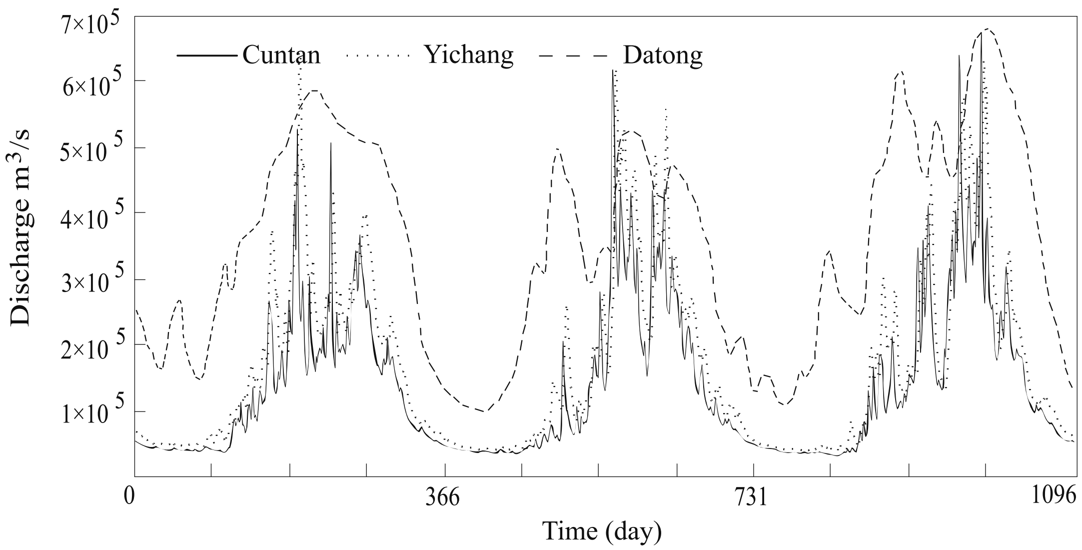

Figure 2 Daily discharge of the Yangtze River at the stations Cuntan, Yichang, and Datong (sample from 1950 to 1952).

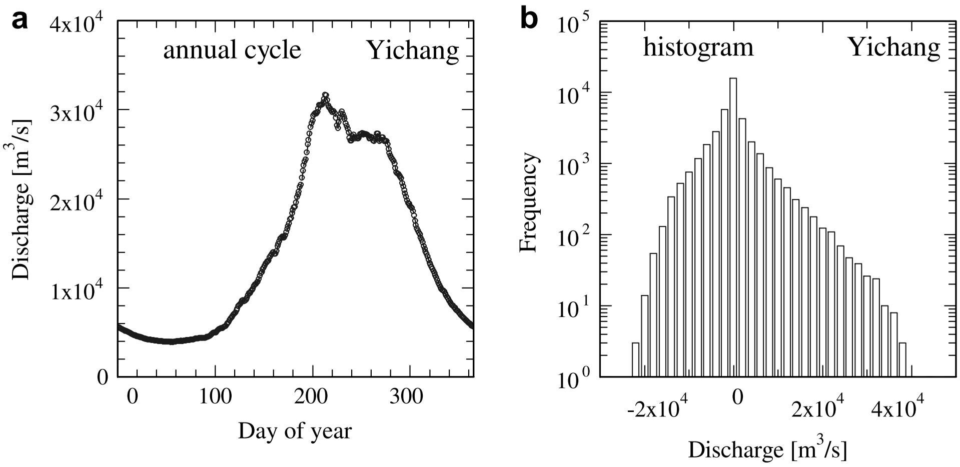

Figure 3 Discharge of the Yangtze at the station Yichang in 1950–2000: (a) annual cycle and (b) histogram of anomalies.

Impact of lake reservoirs

A possible cause of the reduced intra-annual variability downstream Datong compared to Yichang is the presence of lakes (see Fig. 1), which lead to reservoirs buffering the Yangtze flow and damping the variability for time scales up to one year. The aim of the following analysis is to quantify the impact of the lake system in terms of a linear filter that describes the delayed discharge downstream.

To construct a simple model for the filter the following assumptions are made: The flow in Datong is the sum of the flow in Yichang and the tributary flows between the two stations. Due to lack of any information about the variability of the tributary flows, we assume that this flow has the same power spectrum as in Yichang. This assumption will be considered after the specification of the model. Furthermore, we assume that all tributaries are filtered in the same way as the main river flow. This is only valid for part of the tributaries; this shortcoming will be discussed after the analysis. The runoff in Yichang is denoted as R_Y and that of the total tributary flow as R_T. A linear filter for the flow R_D in Datong is

$$R_D(t) = \int_{-\infty}^{\infty} d\tau [R_Y(t-\tau) + R_T(t-\tau)] F_l(\tau) \quad (1)$$

with a filter $F_l(\tau)$ describing storage and release on time scales $\tau > 0$ (note that $F_l(\tau<0) = 0$).

The mean flows of the tributaries and at Yichang are related by $\langle R_T \rangle = c \langle R_Y \rangle$ with $c \approx 1.05$; Chen et al. (2001) estimate the tributary contribution as 50% of the total flow. According to the Wiener–Khinchin theorem the power spectra are

$$S_D(f) = [S_Y(f) + S_T(f)] H_l(f) \quad (2)$$

where $H_l(f)$ is the power spectrum of the filter $F_l(t)$. Since we assume that the tributaries have the same spectral properties as the flow in Yichang, the spectrum of the tributaries is $S_T(f) = (\sigma_T^2/\sigma_Y^2) S_Y(f)$. The variance σ_T^2 of the tributary discharge is estimated by $\sigma_T^2 = \sigma_D^2 - \sigma_Y^2$ with the variance σ_Y^2 at Yichang and σ_D^2 at Datong. Note that spectra S_T, which decay

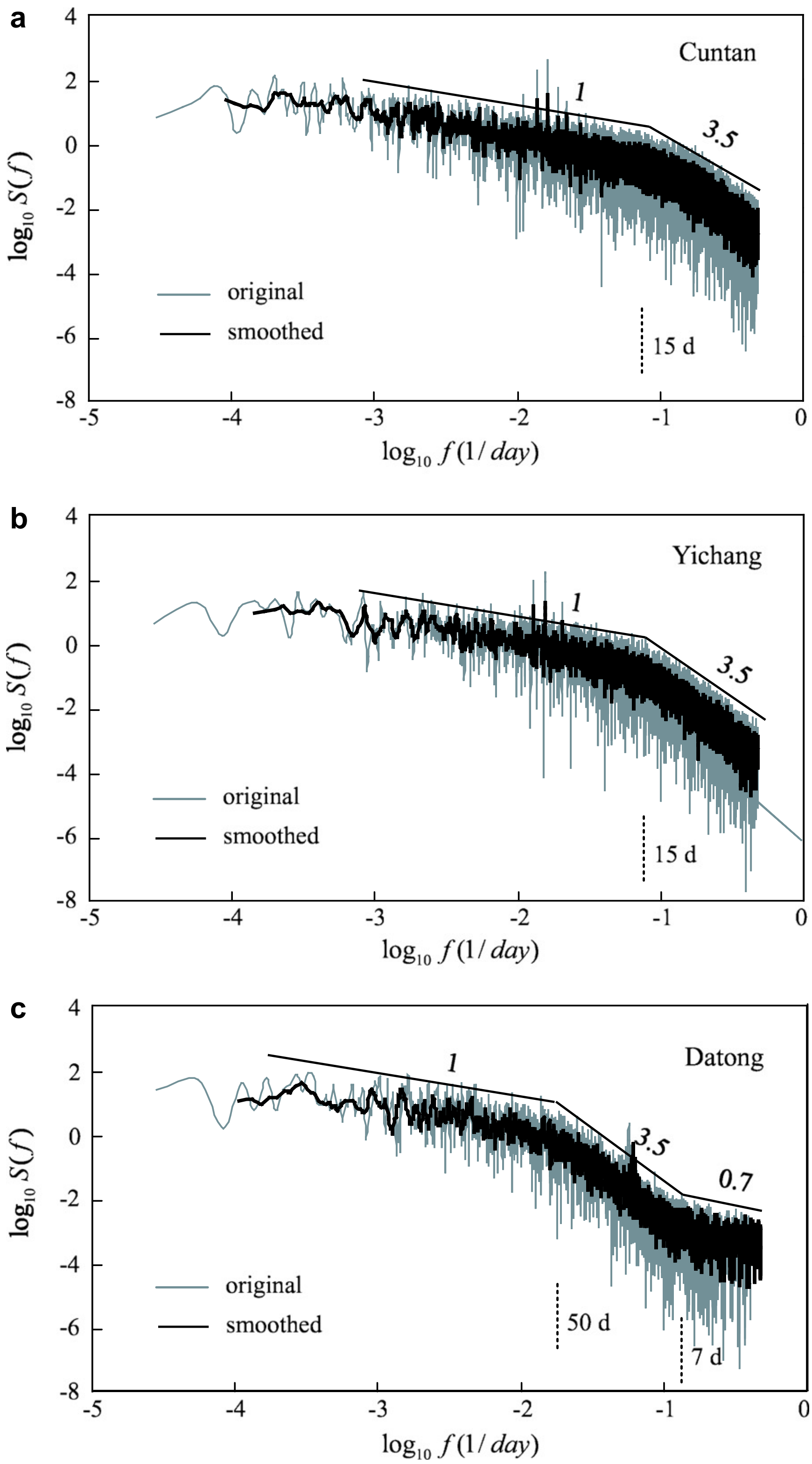

Figure 4 Power spectra (grey) of the Yangtze River discharge at the stations (a) Cuntan, (b) Yichang, and (c) Datong (the black lines are 5-point running means). Slopes indicate power-laws $S(f)\backslash f^{-\beta}$ with the corresponding exponents β obtained by rounded fits.

more rapidly than S_Y, do not impact the characteristics of the filter function according to this simple model. The power spectrum of the filter $F_l(\tau)$ is given by $H_l(f) = |\tilde{F}_1(f)|^2$ where $\tilde{F}_l(f)$ is the Fourier-transform of $F_l(t)$. Using (2) and the spectra in Fig. 4 yields the power spectrum $H_l(f)$ of the lake filter (Fig. 6), which eliminates intermediate frequencies with maximum reduction near 10 days.

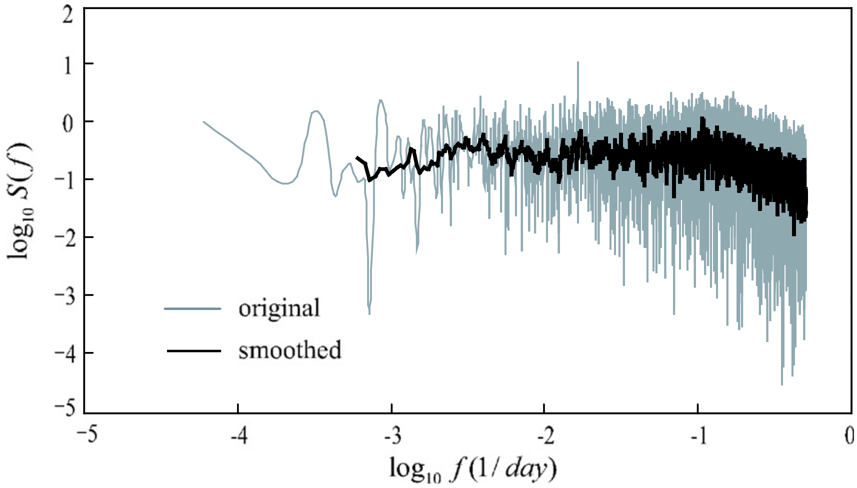

Figure 5 Average power spectrum (grey) of the precipitation in the upper reaches of the Yangtze based on 68 stations during 1960—2004 (the black line is a 5-point running mean).

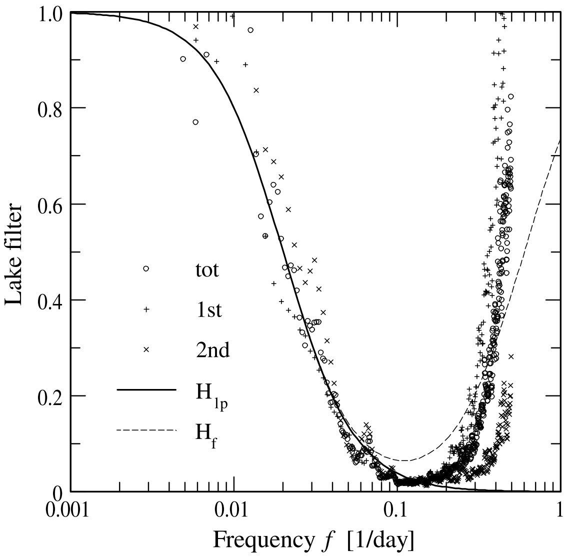

Figure 6 Spectrum $H_l(f)$ of the lake filter compared with $H_f(f)$ of the filter model (dashed line) and its low-pass part $H_{lp}(f)$ (solid line). The observed filters are obtained in the total period (1950—2000, ○), and in the first (+) and the second half (×) of this period.

The observed filter H_l can be approximated by a combination of a low and a high-pass filter. The spectrum of a common low-pass filter with cut-off frequency f_1 is given by

$$H_{lp}(f) = \frac{1}{1 + f^2/f_1^2} \tag{3}$$

and the spectrum of a high-pass filter with the cut-off frequency $f_2 > f_1$ is

$$H_{hp}(f) = 1 - \frac{1}{1 + f^2/f_2^2} \tag{4}$$

The spectrum of the filter model is $H_f = H_{lp} + H_{hp}$. In Fig. 6 the observed filter spectrum $H_l(f)$ in 1950—2000 is compared with those obtained in the first and the second half of the total period. While the low frequency part does not depend on the time interval, the high pass filter shows distinctly lower values in the second half of the period (Fig. 7). This reduction is due to reduced high frequency variability at Datong in the second half of the period (Fig. 7b) which is caused by human activities such as lake reclamation and dike building. A fit reveals the cut-off frequencies $f_1 \approx 0.02$/day and $f_2 \approx 0.6$/day (see Fig. 6).

Note that the presence of the high pass filter is an artifact of the simple model which is due to the unfiltered tributary flows past the last lake, Lake Poyang. The impact of the intermediate reservoirs can be identified with the low-pass filter $F_{lp}(\tau) = \pi f_1 \exp(-2\pi f_1 \tau)$ for $\tau > 0$, which corresponds to (3). Thus, the lakes act as an exponential low-pass filter with decay time $T_1 = 1/(2\pi f_1)$ of about one week (≈8 days).

Summary and conclusions

The intra-annual variability of the daily Yangtze discharge is analysed at the stations Cuntan and Yichang located in the upper reaches and Datong in the lower reach. The power spectra at Cuntan and Yichang follow $S(f) \sim 1/f$ within time scales from two weeks up to a year, and at Datong $\beta = 3.5$, between a week and two months; below a week we obtain $\beta = 0.7$. Since the time series with 1/*f*-spectra are nonstationary, the application of statistical forecast methods is inhibited within timescales up to one year. The previously found inter-annual long-term memory spectrum with (Blender and Fraedrich, 2006) and the intra-annual 1/*f*-spectrum constitute a two-regime behavior of the flow variability, separated by the annual cycle.

The variability of the flow at Datong is explained by storage and delayed release in the extended lake system, which is connected to the Yangtze. A simple linear low pass filter suggests that the flow at this station responds to the input in Yichang within a time scale of one week. Due to the impact of the lakes, the regime behavior differs in the upper and the lower reaches.

The 1/*f*-variability in the upper reaches cannot be related directly to precipitation in this region since its spec-

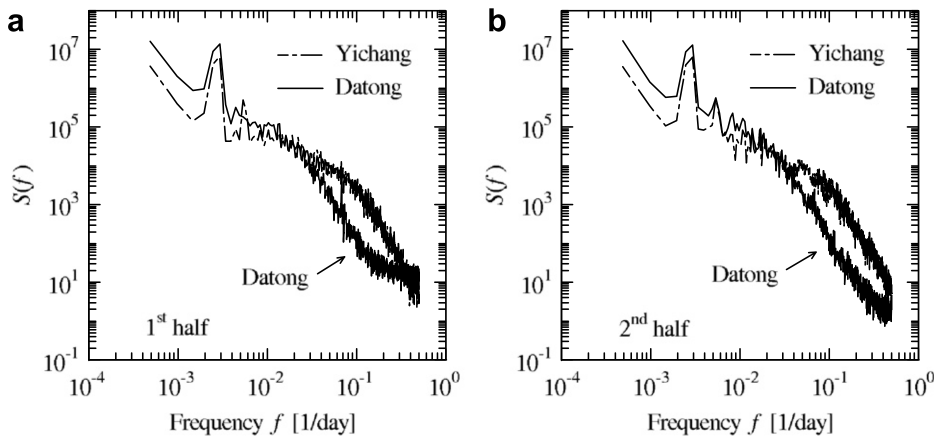

Figure 7 Power spectra of the Yangtze River discharge at the stations Yichang and Datong during (a) the first half and (b) the second half of the period 1950–2000.

trum is white, in agreement with previous findings in other regions. Therefore, further mechanisms have to be considered which introduce the necessary broad spectrum of time scales in the upper reaches. Due to its high streamflow velocities of 1–2 m/s (Chen et al., 2001), the flow in the Yangtze cannot be the source of the spectral power at monthly time scales. As a mechanism of memory beyond one year soil moisture storage has been suggested. The baseflow (groundwater streamflow) flow can introduce memory with broadly distributed monthly time scales.

The spectral variability of river discharges shows very different short and long-term characteristics (Kantelhardt et al., 2006; Koscielny-Bunde et al., 2006). This distinct non-universal behavior is not understood but attributed to the catchment topographies, network geometries, and groundwater flows since precipitation is found to be uncorrelated (spectrally white) world-wide. This paper attempts a quantitative explanation of the river discharge variability along the Yangtze by the interaction with an extended lake system. Similar approaches might be useful for assessing human impacts on natural flows due to hydrological facilities.

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