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Long-term meteorological and hydrological dryness and wetness conditions in the Zhujiang River Basin, South China

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Abstract

Floods and droughts are frequently causing large economic losses in China. These conditions vary in space, time, and magnitude. In this study, long-term meteorological and hydrological dryness and wetness conditions are analyzed for the Xijiang River Basin which is the largest tributary of the Zhujiang (Pearl) River. A very similar inter-annual course of precipitation and discharge can be observed. The standardized precipitation index (SPI) is used to show dryness and wetness pattern in the six sub-basins of the Xijiang River. The SPI-24 correlates high with the standardized discharge index (SDI-24) for Gaoyao hydrological station at the mouth of Xijiang River. Distinct long-term dryness and wetness sequences are found in the time series for the SPI-24 and SDI-24. The principal component analysis reveals many spatial interdependencies in dryness and wetness conditions for the sub-basins and explains some spatio-temporal disparities. Moderate dryness conditions have a larger spatial impact than moderate wetness conditions in the sub-basins. The loading pattern of the first principal component shows that the correlation with the entire Xijiang River Basin is highest in the eastern and lowest in the western sub-basins. Further spatial dipole conditions explain the spatio-temporal heterogeneity of dryness and wetness conditions. Accordingly, the precipitation in the eastern sub-basins contributes more to the hydrological wetness conditions than in the western sub-basins, which mainly contribute to dryness patterns.

The spectral analysis for the SPI-24 (entire Xijiang River Basin) and SDI-24 shows similar peaks for periods of 11–14.7 yr, 2.8 yr, 3.4–3.7 yr, and 6.3–7.3 yr. The same periods can be found for the SPI-24 of Xijiang River's six sub-basins with some variability in the magnitude. The wavelet analysis shows that the most significant periods are stable over time since the 1980s. The extrapolations of the reconstructed time series do not suggest any spatial or temporal changes in the occurrence of dryness and wetness conditions in the next two decades but a continuation of the observed cycles at given magnitude. It can be concluded that long-term hydrological dryness and wetness conditions are directly caused by periodic cycles of meteorological conditions (i.e.

precipitation). The applied methodologies prove to be able to identify spatial interdependencies and corresponding regional disparities, and to detect significant periodicities in long-term dryness and wetness conditions in the Xijiang River Basin.

1 Introduction

Spatio-temporal changes in dryness and wetness patterns have been observed for large areas in China for the past 50–60 yr since the meteorological observation network has been extended. China is influenced by complex atmospheric circulation regimes that result in diverse precipitation patterns which cause more frequent meteorological weather risks such as extreme droughts or serious floods than in other parts of the world (Bordi et al., 2004). Decadal sequences of flood and drought years are historically documented for China, including the Huanghe (Yellow) River, the Yangtze River, and the Zhujiang (Pearl) River. A significant share of the global economic losses due to floods in the last decades has been recorded in China. According to the Munich Reinsurance (Berz and Kron 2004), the floods on the Yangtze and Songhua Rivers in 1998 and the 1996 floods on the Yangtze, Huanghe and Huaihe rivers caused material damages of 30.7 billion USD and 24 billion USD, respectively (nominal 1998 and 1996 price level). Droughts in the north, northeast, and southwest of China in 2009 have caused about 18 billion USD direct economic losses.

Regional climate characteristics and the spatio-temporal variation of dryness and wetness in China have been described nationally (Zhai et al., 2010a,b), regionally (Bordi et al., 2004; Zhai and Qi, 2009), and on basin scales (Zhang et al., 2005; Gemmer et al., 2008; Fischer et al., 2011, 2012a, b). The highest number of articles on observations of precipitation and river discharge in China are available for the Yangtze and the Yellow River, describing how precipitation patterns and surface hydrology have changed. For example, Zhai et al. (2010b) show changes to more dry conditions and their impacts on the stream flow in the western regions of the yellow and Yangtze Rivers in the past 50 yr, while Liu et al. (2011) describe a projected increase in spring/summer

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precipitation and corresponding stream flow of the Yellow River for the 21st century. In the past few years, more literature on these topics has been made available for the Zhujiang River.

The Zhujiang River Basin is located in subtropical, Southern China. This third largest river basin in China is home to more than 160 million people. The population and industrialization have been increasing in recent decades, thus the damage potentials of extreme climate events and other natural disasters have risen (Feng et al., 2007; Fischer et al., 2011, 2012a, b; Gemmer et al., 2011). Precipitation and discharge in the Zhujiang River Basin with its tributaries is an important field of study in order to understand their interaction and consequences.

As many other large rivers in China, the Zhujiang River is characterized by dams. The total storage capacity of reservoirs in the basin had reached 65 km^3 by 2005, which is 23 % of the annual water discharge of the Zhujiang River (Dai et al., 2008). Annual water discharges are mainly influenced by precipitation variability, while the construction of reservoirs/dams in the Zhujiang River Basin had little influence on water discharge (Zhang et al., 2008). As precipitation variability has the highest impact on water discharge, recent findings on precipitation trends, climate extremes, and change points (Fischer et al., 2011, 2012) suggest that the hydrology in the Zhujiang River Basin has also changed. Xu et al. (2010b) indicated that annual discharge of the Zhujiang River correlates well with basin-averaged precipitation. However, Gemmer et al. (2011) have observed increasing tendencies to dryer conditions and stronger precipitation intensities for the Zhujiang River Basin from 1961 to 2007. Fischer et al. (2011) have observed increased numbers of dry days and Zhang et al. (2009) confirmed a tendency to drier conditions in the west of the basin. Another study suggests that the Zhujiang River has the largest human footprint of the 10 largest river basins in South and East Asia (Varis et al., 2011). The assessment of observations in climatological and hydrological time series has delivered some results already showing spatio-temporal changes of stream flow in the past 50 yr, mostly on annual scale. The characteristics and frequencies of

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long-term droughts and wetness conditions in the Zhujiang River Basin have yet to be explained.

Most of the studies mentioned above employed standard methods for assessing spatio-temporal changes in annual, seasonal, monthly precipitation and discharge, and their trends, e.g. the standardized precipitation index or aridity index, and nonparametric trend tests. In this manuscript, we place a broader view of long-term dryness and wetness period fluctuations (1961–2030) in the Xijiang River Basin of the Zhujiang River Basin using the standardized precipitation index which is recommended by the World Meteorological Organization (WMO) to characterize meteorological droughts (Klein Tank et al., 2009). The standardized discharge index is employed to characterize hydrological dryness and wetness conditions in order to analyze how long-term precipitation patterns have impacted the discharge of the river and to evaluate the characteristics of long-term climatological and hydrological dryness and wetness conditions.

2 Regional settings, data, and methods

2.1 Regional settings

The Zhujiang River Basin in subtropical South China (Fig. 1) covers an area of approximately 450 000 km^2 with a population of more than 160 million. The region is currently one of the most economically prosperous areas of China, with very high development rates, and one of China's highest GDP per capita of more than 40 000 CNY per year (National Bureau of Statistics of China: www.stats.gov.cn). Since the 1950s, approximately 9000 dams with a reservoir storage capacity of 65 km^3 have been constructed (Dai et al., 2008; Waterpub, 2012). In 2008, the Longtan hydropower station, China's third-largest with an estimated capacity of 4.9 GW, started operation in the upper reaches of the Hongshui River (China Daily, 2008).

The largest tributary of the Zhujiang River is the Xijiang (West) River, which accounts for 78 % of the total drainage area of the Zhujiang River Basin. At Gaoyao hydrological

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station the daily average discharge of the Xijiang River is observed. To examine an even higher level of spatial differentiation, the Xijiang River Basin is subdivided into its six sub-basins (Beipan, Nanpan, Yujiang, Hongshui, Liujiang, and Lijiang, see Fig. 1). Due to the availability of discharge data at Gaoyao and the high importance in total drainage, the Xijiang River Basin and its six sub-basins are examined on their long-term climatological and hydrological dryness and wetness conditions.

2.2 Data

Daily precipitation data of 118 weather stations in the Xijiang River Basin (Fig. 1) for the period 1961–2007 and daily average discharge data of the hydrological station at Gaoyao on the Xijiang River for the period 1961–2006 are used. The data sets were provided by the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). The data sets were controlled on their quality by the NMIC (Qian and Lin, 2005). The NMIC checked the data on homogeneity using the departure accumulation method (Buishand, 1982). Less than 0.1 % of data gaps appear in the daily precipitation records.

2.3 Methods

2.3.1 Standardized precipitation and discharge indices (SPI and SDI)

Weighted area averages in precipitation are calculated for six sub-basins (Fig. 1) of the Xijiang River Basin using the Thiessen polygon method provided within the ArcGIS software package. This method is a common approach for modelling the spatial distribution of rainfall based on station observations (Jiang et al., 2007). Here, for each sub-basin, the areal percentage of each Thiessen polygon within its boundary is used to determine the weight of each station's total precipitation and standardized precipitation index (SPI). This is used to calculate the weighted area average annual precipitation and monthly SPI for the according sub-basin. Following this, the areal percentages

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of the six sub-basins of the Xijiang tributary are used to calculate the weighted area average annual precipitation and monthly SPI for the entire Xijiang River Basin.

The SPI is calculated using the statistical software R, to quantify dryness and wetness periods (McKee et al., 1993). It is a meteorological index using monthly precipitation data (Mishra and Singh, 2010). Comprehensive descriptions on the SPI and its application in China are available, e.g. from Bordi et al. (2004), Zhang et al. (2009), Zhai et al. (2010a,b), and Zhao et al. (2011). In our analyses, we consider the categories of the SPI/SDI values according to Lloyd-Hughes and Saunders (2002), who defined the values at −1.00 to −1.49 as moderate drought (−1.50 to −1.99 as severe drought, and −2 or less as extreme drought), and the values at 1.00 to 1.49 as moderately wet (1.50 to 1.99 as severely wet, and 2 or more as extremely wet). In this study, the SPI is calculated with weighted area averaged monthly precipitation data at a 24-months scale (SPI-24), which is suitable for the determination of meteorological and hydrological long-term dryness and wetness conditions (Bordi et al., 2004).

The standardized discharge index (SDI) is performed in an analogous manner to the SPI. It contains monthly discharge data instead of precipitation data and expresses hydrological excess or deficit availability of water. McKee et al. (1993) suggested the application of the SPI procedure to other water variables, such as observed discharge data. Hence, the method can be derived from McKee et al. (1993), Nalbantis and Tsakiris (2009), and Mishra and Singh (2010), although the respective terminology and input data vary in each of the manuscripts. To our best knowledge, the SDI has not been applied in the Zhujiang River Basin yet. In this study, the SDI is calculated with averaged monthly discharge data at a 24-months scale (SDI-24).

2.3.2 Principal components analysis

The principal component analysis (PCA) is broadly used for identifying patterns in climate data and to highlight their similarities and differences (Santos et al., 2010). We use the PCA to sum up the spatial patterns of co-variability of dryness and wetness according to the SPI-24 series at different stations. A set of linearly independent spatial patterns (loadings) are generated, which describe the correlations with the specific principal components (PC). The PCA is introduced by Bordi et al. (2004, 2007) and Zhao et al. (2011), and calculated by using the statistical software R.

2.3.3 Power spectrum and continuous wavelet analysis

The fast Fourier transform is used to generate the power spectrum of the signal in the monthly time series (Schönwiese, 2006; Wilks, 2006). The significant periodicities embedded in the time series can be determined based on the amplitude of the corresponding signal. Similarly, a continuous wavelet transform is used to break up the signal into shifted and scaled versions of the original wavelet by decomposing a time series into a time-frequency space (Torrence and Compo, 1998). In this study, we apply the Morlet wavelet, which is the most commonly used continuous wavelet transform to visualize the amplitudes in the time-frequency space. All calculations are done by using related packages of the statistical software R. The results can be used to detect periodicities and their changes in time (i.e. time-frequency relationships) in climatological datasets. Gao et al. (2010) used the continuous wavelet transform likewise in order to assess the fluctuation of monthly observed and projected average stream flows (return periods of extremes) in the Huaihe River Basin in China. Becker et al. (2008) determined quasi periodicities of extreme precipitation events in the Yangtze River Basin by employing the continuous wavelet analysis.

2.3.4 Extrapolation

The SPI-24 and SDI-24 time series are extrapolated between 2007 and 2030 in order to determine the periodicity of dryness and wetness conditions. We apply the fast Fourier transform again, but this time only to the significant periodicities indentified in the power spectrum. The estimation of future monthly values follows an optimization and extrapolation process for the observed time series as developed by Bordi et al. (2004). We use the parameterized software autosignal. The predicted values are generated based

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on the assumption that the significant periods are stable in time, i.e. the periodicity is similar for the following two decades (Becker et al., 2008). In order to characterize the reliability of this assumption, the results of the wavelet analyses are investigated on the stability of the significant periods.

3 Results

3.1 Relationship between precipitation and discharge

Figure 2 shows the time series of area averaged annual precipitation in the Xijiang River Basin and the mean annual discharge at Gaoyao hydrological station from 1961 to 2006. The annual average precipitation is about 1350 mm and the inter-annual variability is 10 % according to the coefficient of variation. Two distinct minima in annual precipitation (below 1100 mm) can be observed for 1963 and 1989. A maximum in precipitation (above 1700 mm) occurred in 1994.

The average discharge between 1961 and 2006 is 7000 $m^3 s^{-1}$ (Fig. 2). The inter-annual variability is 19 %. Two minima in discharge (below 5000 $m^3 s^{-1}$) appeared simultaneously with the precipitation minima (1963, 1989). Two maxima (above 10 000 $m^3 s^{-1}$) can be observed in 1968 and 1994. A strong correlation (0.88) is found for the monthly area averaged precipitation and monthly discharge at Gaoyao station from 1961 to 2006.

Figure 3 shows the average monthly precipitation in the Xijiang River Basin and the average monthly discharge at Gaoyao hydrological station for the period 1961–2006. The monthly precipitation maximum occurs in June with nearly 250 mm. The highest monthly average discharge can be measured in July with nearly 16 000 $m^3 s^{-1}$. The distinct seasonality is also expressed in this figure with a distinct dry period from November to March, with monthly precipitation of less than 50 mm and monthly discharge minima of less than 4000 $m^3 s^{-1}$. The highest inner-annual variability of monthly precipitation can be observed in December with 69 %, while the highest monthly variability of discharge is in March (64 %). The high percentages are mainly due to the low average values of these months.

For illustration purposes, the monthly precipitation and discharge values of 1963 and 1994 are shown Fig. 4. In comparison with the long-term average, much less (more) precipitation and discharge was observed in 1963 (1994), especially in the summer months from May to August. Precipitation and discharge amounted for 50–80 % less in 1963 and 30–60 % more in 1994.

This section underlines the strong correlation between the monthly area averaged precipitation and monthly discharge. Based on the monsoon climate in the research area, the innerannual variability of precipitation and discharge appears natural, the latter following the course of the former. It is of high interest whether the interannual variability of precipitation and discharge are short term or lead to long-term dryness and wetness conditions, both in hydrological and meteorological terms. The magnitude and periodicity of dryness and wetness and their interrelation are analyzed in the following.

3.2 Relationship between SPI-24 and SDI-24

Figure 5 shows the area averaged SPI-24 weighted for the Xijiang River Basin and the SDI-24 for Gaoyao Hydrological Station. The SPI-24 (Fig. 5 upper panel) reveals that wet conditions (SPI values > 1) prevailed for about 20 yr after a drought (SPI values < -1) ended in 1965. Uninterrupted dryness conditions at different magnitudes characterized the period 1985–1995. The wetness conditions after 1995 are again nearly uninterrupted for 10 yr. After 2004, a sequence of dryness conditions prevailed in the basin. The most distinct peaks in wetness conditions occurred around 1974 and 1995. Peaks in dryness conditions occurred around 1964, 1990, and 2005.

The SDI-24 (Fig. 5 lower panel) is very similar to the corresponding SPI-24 and takes the same chronological positive and negative course. The peaks and durations of climatological dryness and wetness conditions in the SPI-24 can simultaneously be found in the SDI-24. The highest peak for climatological drought around 1964 for instance is also the most severe hydrological drought. The coefficient for the correlation

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between the average SPI-24 for the weighted sub-basins and the corresponding SDI-24 is 0.94.

The identified peak years in SPI-24/SDI-24 are chronologically similar to the maxima and minima in the annual total precipitation and annual average discharge (cf. Fig. 2). The SPI-24/SDI-24 reveals long-term dryness and wetness conditions for the Xijiang River Basin. The strong similarities imply a very high influence of natural precipitation pattern on the discharge, which can be spatially determined and explained by investigating the SPI-24 of the six sub-basins.

The SPI-24 for the six sub-basins is illustrated in Fig. 6. Sequences of wetness and dryness vary in the sub-basins. In general, the sub-basins take the same course as the averaged SPI-24 for the entire basin (Fig. 5). However, the wetness conditions after 1965 are more distinct (1) in magnitude for the Beipan sub-basin (northwest) and (2) in duration for the Nanpan sub-basin. Beipan shows a more distinct magnitude in the drought of the early 1990s whereas it was longer in, e.g. the Liujiang sub-basin (southeast).

Focusing on moderate wetness conditions (SPI > 1) and dryness conditions (SPI < -1), one can see that the droughts around 1965, 1990 and 2005 were simultaneously measured in all six sub-basins. The less distinct drought around 1986 was measured in 50 % of the sub-basins. Most of the moderate wetness conditions were simultaneously recorded in 2–3 of the sub-basins only (e.g. 1983, 2003). The wetness around 1975 occurred in 5 of the sub-basins, but moderate wetness conditions were never recorded in all of the six sub-basins at the same time. Figure 6 underlines the distinct spatial variability of dryness and wetness sequences which can well describe the averaged SDI-24 and show that moderate dryness conditions have a larger spatial impact than moderate (and higher) wetness conditions.

The correlation coefficient between the SPI-24 for each sub-basin and the SDI-24 varies between 0.65 (Beipan) and Hongshui and Yujiang (each 0.82). This suggests that each sub-basin has a considerable impact on the SDI-24 at Gaoyao hydrological station, but some sub-basins contribute higher to the discharge.

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Conclusively, changes in the SDI-24 can be profoundly explained by the average SPI-24 weighted for the sub-basins. We have identified distinct long-term dryness and wetness conditions in the Xijiang River Basin. To determine the temporal characteristics of dryness and wetness and their changes, we analyze their frequencies in the following.

3.3 Peak dry and wet periods

Frequencies of peak (moderate) dry and wet conditions (SPI < −1 and SPI > 1) can be explained in different ways. Here, the duration and magnitude of dryness and wetness are of highest concern. The duration of wet and dry conditions is regarded as being scattered if the values fall below a given threshold (Mishra and Singh, 2010). Four distinct moderate drought events and four slightly less distinct wetness periods are found for the entire time period from 1963 to 2006 (Fig. 5). Distinct drought events occurred during 1963–1965, 1988–1990, 1990–1992, and 2004–2006. In summer 1990, a relatively wet period of few months separates the two distinct drought events. The moderate wetness events (1968–1970, 1974/75, 1994–1996, and 1997/98) show a higher disparity between the sub-basins, i.e. most events occur only in half of the sub-basins (Fig. 6).

Table 1 shows the duration (in months) and the magnitude (as sum of SPI-24 or SDI-24) of hydrological and meteorological dryness and wetness according to the SPI-24 and SDI-24 for conditions below −1 (moderate dryness) and above +1 (moderate wetness) only. Most of the meteorological dryness conditions occurred in the sub-basins, the entire Xijiang River Basin, and Gaoyao at the same time periods while the wet periods are less developed. However, as can be seen, the 1963–1965 dryness in the SDI-24 for instance had the same duration as the 1988–1990 dryness, but was higher in magnitude. The 2004–06 drought ranks third both in duration and magnitude. The SPI-24 corresponds likewise. The longest and highest wetness conditions in the SDI-24 occurred in the 1990s. 1994–1996 shows the longest and highest wetness conditions in both the SDI-24 and SPI-24.

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Regarding each sub-basin's role in contributing to the intensity of the hydrological dry or wet conditions at Gaoyao, for each examined dryness or wetness event different sub-basins contributed varyingly strong (Table 1). For example, the drought event in 1963–1965 occurred longer and stronger in the eastern sub-basins; hence those were supporting the long duration and high magnitude discharge at Gaoyao with a higher proportion. Contrarily to that, the long drought event at Gaoyao in 2004–2006 was very strongly affected by the more than two-year drought in Beipan. It can be also seen that all of the sub-basins contributed to dryness conditions to a higher or lower extent, while proportionately the (north-)eastern sub-basins contribute stronger to the wetness conditions at Gaoyao.

The SPI-24 values of the sub-basins of Xijiang River have each a certain share of the dryness and wetness conditions at Gaoyao hydrological station. This finding will be further investigated and specified with the principal components analysis (PCA) in the following.

3.4 Principal component analysis of SPI-24

PC scores are investigated in order to illustrate the spatio-temporal variability of dryness and wetness conditions in the Xijiang River Basin that have been described above. The PC scores of the SPI-24 are displayed in Fig. 7. The first three loadings explain 92 % of the variance. PC-1 (Fig. 7a) explains 67 % and shows multi-year fluctuations. PC-2 shows a higher frequency of negative values and describes 14 % of the variance (Fig. 7b) whereas PC-3 falls below 11 % with balanced positive and negative values (Fig. 7c). As expected, the magnitude of all PC scores is highest in PC-1 given the high percentage. PC-3 shows a higher tendency to dryness in magnitude and duration as compared to PC-2.

The loading patterns (linearly independent spatial pattern) of PC-1, PC-2, and PC-3 in each of the sub-basins are displayed in Fig. 8. In Fig. 8a, the correlation between the sub-basins' PC-1 loading and the averaged PC-1 loading is highest in Liujiang sub-basin. Nevertheless, the loading of PC-1 is spatially homogeneous in the Xijiang River

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Basin. The loading of PC-2 (Fig. 8b) is negative for three sub-basins in the east and positive in the west. PC-3 (Fig. 8c) also reflects a dipole pattern but from south to north. These dipole conditions explain the opposing course of the sub-basins' SPI-24 in some few years (especially in the mid-1980s) and the difference in magnitude in others.

The PCA's loading patterns describe a generally good spatial homogeneity of the appearance of dryness and wetness conditions in the Xijiang River Basin. Spatially heterogeneous appearance of dryness and wetness in some years can be explained by the loading patterns. In the following, we investigate the periodicity of the peak dryness and wetness conditions that have been detected spatially and temporally.

3.5 Periodicities of SPI-24 and SDI-24

The results of the spectral analysis (Fig. 9) show similar peaks in the SPI-24 and the SDI-24. The highest peaks (power magnitude) for the SPI-24 and SDI-24 are located between 0.006 and 0.008 representing significant frequencies (at 90 % confidence level) at 11–14.7 yr periods. Lower peaks are found at frequencies of 2.8 yr, 3.4–3.7 yr, and 6.3–7.3 yr. The magnitude of the peaks varies slightly between the SPI-24 and SDI-24. This underlines that the dryness and wetness conditions are subject to distinct periodic reoccurrence and that the cycles in the SPI-24 dominate cycles in the SDI-24.

The results of the spectral analysis for the six sub-basins of Xijiang River are shown in Fig. 10. All sub-basins show the most significant (at 90 % confidence level) peaks located at 11 and 14.7 yr periods. In the Beipan and Nanpan sub-basins, the 11 yr peak is much stronger. The 14.7 yr period is the strongest in the other four sub-basins. Other peaks are similar to those for the SPI-24 and SDI-24. However, Yujiang sub-basin is the only watershed with a distinct peak at 3.7 yr which is nearly as high as that for the 11–14.7 yr period. Lower peaks are found at frequencies of 2.8 yr, 3.4–3.7 yr, and 6.3–7.3 yr for all sub-basins. These periods highlight consistency with the periods in the SPI-24 of the entire Xijiang River Basin and the SDI-24 of Gaoyao hydrological station with some variation in magnitude.

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Figure 11 shows the results of the wavelet analyses of the SPI-24 (entire Xijiang River Basin) and the SDI-24. As can be seen, the significant periodicity in the SPI-24 and SDI-24 with 11–14.7 yr frequency is stable over time since the 1980s and has the highest significance in the 1980s and 1990s. The peak in the SPI-24 of 3.4–3.7 yr frequency shifts slightly over time after the 1980s. It loses some significance in the late 1990s and shifts to a slightly lower frequency.

As the PCA suggests spatial disparities in dryness and wetness conditions, we analyze the wavelet pattern of the SPI-24 over the sub-basins (Fig. 12). The 11–14.7 yr frequency is apparent for all sub-basins and is stable over time and in intensity except for Yujiang. The latter is apparently dominated by the frequency of 3.7 yr. The sub-basins Beipan and Hongshui for instance are dominated by the 11–14.7 yr frequency over the entire time series whereas the frequency has slightly longer periods in the Hongshui sub-basin. The frequency of 3.4–3.7 yr is also most persistent in the Hongshui sub-basin. The sub-basins located in the south and east (Yujiang and Lijiang) lack significant periodicities in the first decade of their time series. The frequency of 3.7 yr in Beipan and Nanpan already eases in the 1960s, whereas in Lijiang and Liujiang it amplifies in the 1990s.

In the following, we extrapolate the significant peaks in periodicity of the spectral analysis assuming that the observed periods that cause dryness and wetness conditions will prevail in the future.

3.6 Extrapolation of SPI-24 and SDI-24

Figure 13 shows the SPI-24 and SDI-24 extrapolated until 2030. The extrapolation of the SPI-24 (entire Xijiang River Basin) is dominated by the significant short-term periodicity of 2.8 and 3.4–3.7 yr, respectively, that can be seen in the reconstructed frequency (black line from 1963 to 2006). The beginning of the extrapolation (from 2007 until 2014) shows a change from slight wetness to moderate dryness conditions. After 2014, the extrapolation points out an increase in SPI-24 values which peak in moderate wetness conditions in 2028 which are then followed by moderate dryness conditions. Likewise, the reconstructed frequency and the extrapolation of the SDI-24 with the observed periodicities show a similar course as the SPI-24.

The reconstructed frequency for each of the six sub-basins (Fig. 14) shows the periodicity that has been detected in the power spectrum. The extrapolation is based on the continuation of the selected periodicities. Distinct spatial disparities in the extrapolation (and reconstruction) of the SPI-24 can be seen. The period 2007–2008 is highlighted by a shift from dry to normal conditions except for Beipan which shows an aggravation of the dryness conditions towards an extreme drought starting in 2008. Based on the periodicity of each sub-basin, the course of the SPI-24 shows different magnitudes and durations in the extrapolations. A 3.7 yr periodicity is most apparent in Yujiang and Hongshui sub-basins. The extrapolation clearly relies on these periods for the two sub-basins whereas the extrapolation for the other sub-basins is controlled by longer periods.

4 Discussion and conclusions

The main interest of this study was to evaluate how long-term precipitation patterns have impacted the discharge of Xijiang River. Therefore, the characteristics of long-term climatological and hydrological dryness and wetness conditions were analyzed. It can be concluded that the discharge of Xijiang River based on its SDI-24 directly relies on the area weighted SPI-24 of the Xijiang River Basin. Hence, the natural variation in precipitation is responsible for the discharge to a very high degree. This is in line with the findings of Zhang et al. (2008), who concluded that the long-term changes of annual water discharge are mainly controlled by precipitation variation, while the construction of reservoirs/dams has made little influence on water discharge in the Zhujiang River Basin. We can also conclude that each sub-basin has a considerable strong impact on the SDI-24 at Gaoyao hydrological station, while some sub-basins contribute higher to the discharge (correlation up to 85 %) than others. With the calculation of the spatial interdependencies of the sub-basins using the PCA, it was possible to determine that all sub-basins contribute to hydrological dryness conditions, while mainly the north-eastern sub-basins can be made responsible for wetness conditions. The western sub-basins have rather little influence in hydrological wetness conditions of Xijiang River. We can also conclude that meteorological dryness conditions are larger in spatial extent (i.e. covering all sub-basins) than wetness conditions.

We found that distinct cycles of dryness and wetness occurred chronologically over periods of several years. The precipitation in the Xijiang River Basin and the discharge of Xijiang River are dominated by significant periods of 11–14.7 yr and significant cycles of shorter periodicity (2.8 yr, 3.4–3.7 yr, and 6.3–7.3 yr). The controlling force of the long-term hydrological status at Xijiang River is therefore an 11–14.7 yr oscillation in the precipitation. Additionally, spatial disparities can be observed in the sub-basins which are an interesting feature but can be explained by regional disparities in annual and monthly precipitation patterns with annual values decreasing from the east to the west of the river basin (Gemmer et al., 2011).

An increase in dry days has been detected by Gemmer et al. (2011) for the same precipitation time series. Furthermore, increases in the magnitude of indices describing dryness, and a prolongation of dry periods with an opposing shortening of wet periods were identified by Fischer et al. (2011). These findings can explain the long-term drought sequences which we observed in the SPI-24 and SDI-24 time series during the second half the observed time period. It might also explain why the short-term periods, around 3–4 yr, shifted to slightly longer periods which would then indicate inner-annual changes. Further noticeable are the change points in precipitation indices in 1985/86 and 2003/04 that have been detected by Fischer et al. (2012b). Both change points mark the start of the two most distinct dryness clusters in the SPI-24 and SDI-24 time series. To some extent, Gemmer et al. (2011) and Fischer et al. (2011, 2012b) link the observed changes to the weakening of the East Asian Summer Monsoon (EASM).

Compared to earlier studies, our approach of analyzing long-term changes and periodicities disaggregates extreme events and allows a broader view on meteorological and hydrological statuses. With the standardization of long-term precipitation cycles, they can be compared with the hydrology. With the understanding of the periods and reoccurring dryness and wetness conditions, it is important to consider the identified periods in any water-related planning.

The extrapolation of the significant periodicities identified in the power spectrum is a statistical prediction obtained through the fast Fourier transform and not based on modelling results from global or regional climate models. It is assumed that the significant periods will pertain in the near future with their extrapolation suggesting certain spatial and/or temporal changes in the occurrence of dryness and wetness conditions in the next two decades, but no obvious tendencies to significantly higher or lower magnitudes. This prediction of no significant trends in regional precipitation pattern in the first three decades of the 21st century can be supported by the findings of Sun and Ding (2010). By using a multi-model ensemble of global circulation models, they projected an increase in summer precipitation for the whole of South China merely starting around the 2040's. Similarly, Fischer et al. (2012a) projected climate extremes in the Zhujiang River Basin, using the regional climate model CCLM, and did not identify any significant trends in precipitation extremes for the period 2011–2050. Furthermore, Zeng et al. (2012) applied the outputs from the global circulation model ECHAM5 to an artificial neural network to project future river discharge of the Yangtze River, but did not identify any obvious trends.

Based on these findings, we can draw the hypothesis that it is more important to investigate periodic events rather than trends or extremes. This hypothesis is fully supported by the statistical approach applied as compared to a physical or dynamical approach based on global or regional climate models. Although we are unable to reliably predict the stability of the periodicities using few statistical spectral-analysis methods (Ghil et al., 2011), we can place more confidence on our short-term extrapolations, as these rely on the observed significant periodicities, than on near-future projections of global or regional climate models (cf. Becker et al., 2008).

In future, nonetheless, a physical based approach can be used to further test this hypothesis at a smaller regional scale, where regional disparities will have to be

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considered. A recent example can be drawn for the Beipan sub-basin. The extrapolation showed distinct extreme dryness conditions in 2008–09 which are spatially and temporally in line with the observed long-term drought that occurred in Southwest China in 2009–2010 (Lü et al., 2012). Here, an anomalous weakening of the vertical Asian monsoon circulation in South Asia has been found responsible for this drought event. The extrapolation for Beipan takes a different course than the other sub-basins, which the newly available statistics prove to be correct. It has yet to be confirmed whether the magnitude of the peaks are precise.

The PCA has shown regional disparities in the SPI-24 of the sub-basins. The area averaged SPI-24 for the Xijiang River Basin agrees well with the SDI-24 and each sub-basin might have different long-term dryness and wetness conditions. At a regional level, any significant changes in the sub-basins will have effect on the discharge and long-term dryness/wetness conditions of Xijiang River. This factor might have been underestimated in previous studies (e.g. Zhang et al., 2008). The method using the weighted SPI-24 for instance shows that Beipan has a distinct impact on Xijiang's hydrology, especially during dryness conditions such as in 2008–2009. Therefore, our methodology proves to be able to detect significant periodicities and to display regional disparities in long-term dryness and wetness conditions.

Our initial investigations on the origin of the long-term dryness and wetness occurrences and the corresponding periodicities did not show any inter-connections with large-scale atmospheric circulation indices (e.g. El Niño–Southern Oscillation, ENSO, Madden-Julian-Oscillation, MJO). Such physical explanations for the observed periodicities are needed to gain more confidences on the future stability of the cycles, and hence, of the reliability of our extrapolation results (Ghil et al., 2011). Studies by Bordi et al. (2004), Fischer et al. (2012b), Gemmer et al. (2011), Lü et al. (2012), and Zhang et al. (2008) suggest that several large-scale atmospheric circulations are responsible for certain changes in the strength of the East Asian Monsoon, which further leads to changing periodicities, change points, and trends in precipitation pattern. Nonetheless, the extrapolation of the significant periodicities in the next decades provides valuable information on the potential occurrence and magnitude of dryness and wetness conditions for such as flood risk forecast and drought preparedness.

This study highlights the close relationship of spatio-temporal meteorological dryness and wetness conditions with hydrological responses. Considering that natural factors are responsible for the variation in precipitation, very little influence of human activities can be found in the monthly characteristics of hydrological processes. Water resource management planning and future research on the projection or prediction of hydrological long-term dryness and wetness conditions in the Zhujiang River Basin should particularly take periodicities in regional precipitation patterns into consideration.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/9/10525/2012/hessd-9-10525-2012-supplement.zip.

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Table 1. Duration and magnitude of peak periods of moderate drought (SPI < −1) and moderate wetness (SPI > 1) in the six sub-basins of the Xijiang River Basin, the entire basin (Xijiang), and at Gaoyao hydrological station (SDI < −1, SDI > 1), 1963–2006.

Event	Period	Duration (months) Nanpan	Beipan	Hongshui	Liujiang	Yujiang	Lijiang	Xijiang	Gaoyao
	1963–1965	14	9	16	20	20	19	18	25
	1988–1990	17	14	11	8	16	3	10	25
	1990–1992	8	11	3	4	5	22	7	20
moderate drought (< −1)	2004–2006	2	27	6	3	6	8	6	22
	event sum	41	61	36	35	47	52	41	92
	1968–1970	0	13	12	7	0	0	0	21
	1974/75	3	0	2	2	8	12	2	11
	1994–1996	0	0	13	20	5	21	12	26
moderate wetness (> 1)	1997/98	0	0	2	3	2	15	1	23
	event sum	3	13	29	32	15	48	15	81
Event	**Period**	**Magnitude (sum of monthly SPI values) Nanpan**	**Beipan**	**Hongshui**	**Liujiang**	**Yujiang**	**Lijiang**	**Xijiang**	**Gaoyao**
	1963–1965	−21.4	−11.3	−23.1	−25.1	−26.8	−24.7	−23.0	−51.0
	1988–1990	−23.0	−25.8	−15.7	−9.5	−21.1	−3.4	−13.1	−35.7
	1990–1992	−8.5	−20.1	−3.2	−4.6	−6.0	−30.5	−7.8	−29.3
moderate drought (< −1)	2004–2006	−3.4	−33.4	−6.4	−3.1	−6.3	−10.2	−6.5	−29.5
	event sum	−56.3	−90.6	−48.5	−42.4	−60.2	−68.8	−50.4	−145.5
	1968–1970	0.0	16.0	13.5	7.7	0.0	0.0	0.0	29.1
	1974/75	3.3	0.0	2.3	2.1	9.2	14.0	2.2	13.5
	1994–1996	0.0	0.0	20.0	35.2	5.3	28.0	14.4	43.8
moderate wetness (> 1)	1997/98	0.0	0.0	2.1	3.4	2.2	18.0	1.0	35.7
	event sum	3.3	16.0	37.9	48.5	16.7	60.0	17.6	122.1

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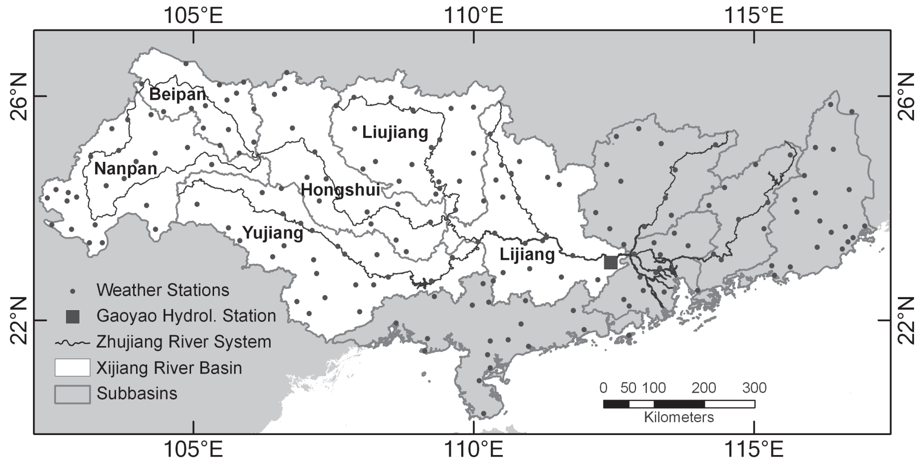

Fig. 1. Location of the six sub-basins in the Xijiang River Basin of the Zhujiang River Basin.

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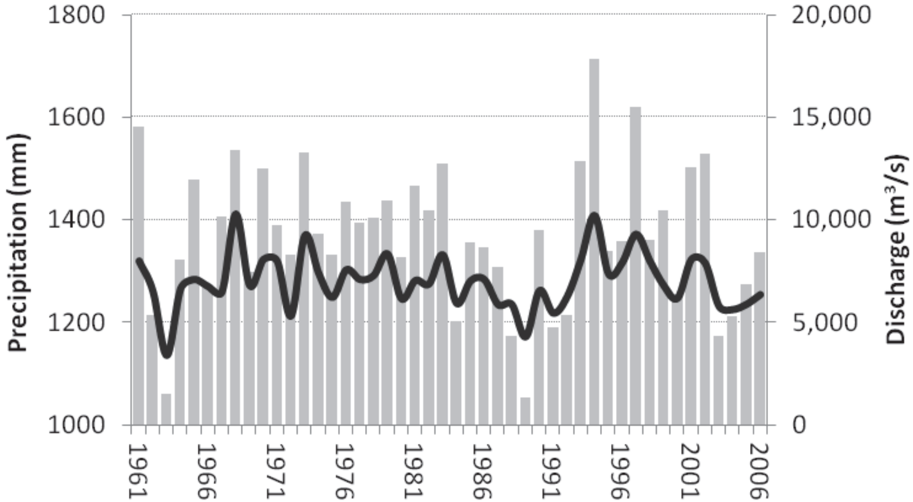

Fig. 2. Annual Precipitation (grey bars) in the Xijiang River Basin and annual discharge (black line) at Gaoyao Hydrological Station 1961–2006.

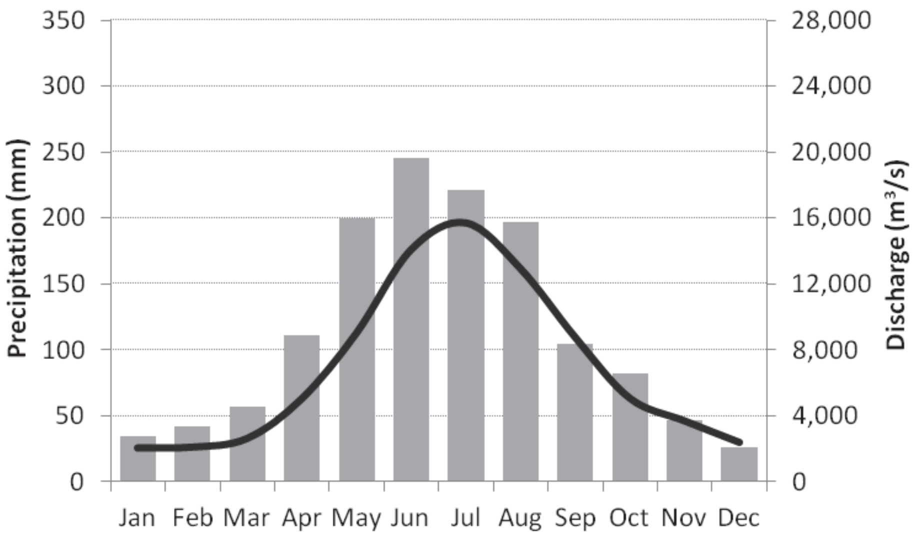

Fig. 3. Average monthly precipitation (grey bars) in the Xijiang River Basin and average monthly discharge (black line) at Gaoyao Hydrological Station 1961–2006.

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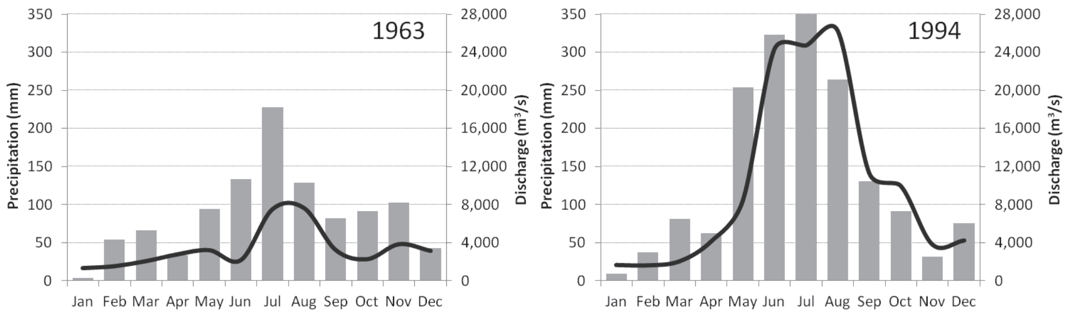

Fig. 4. Average monthly precipitation (grey bars) in the Xijiang River Basin and average monthly discharge (black line) at Gaoyao Hydrological Station in 1963 (left) and 1994 (right).

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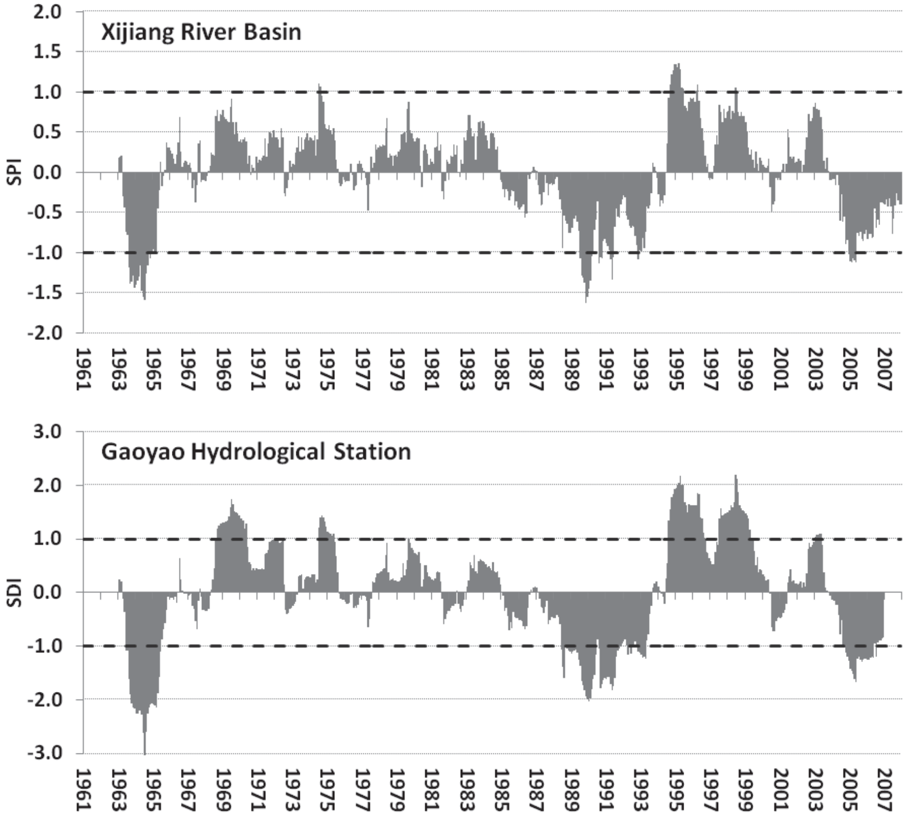

Fig. 5. SPI-24 of the Xijiang River Basin (upper panel) and the SDI-24 of Gaoyao Hydrological Station (lower panel).

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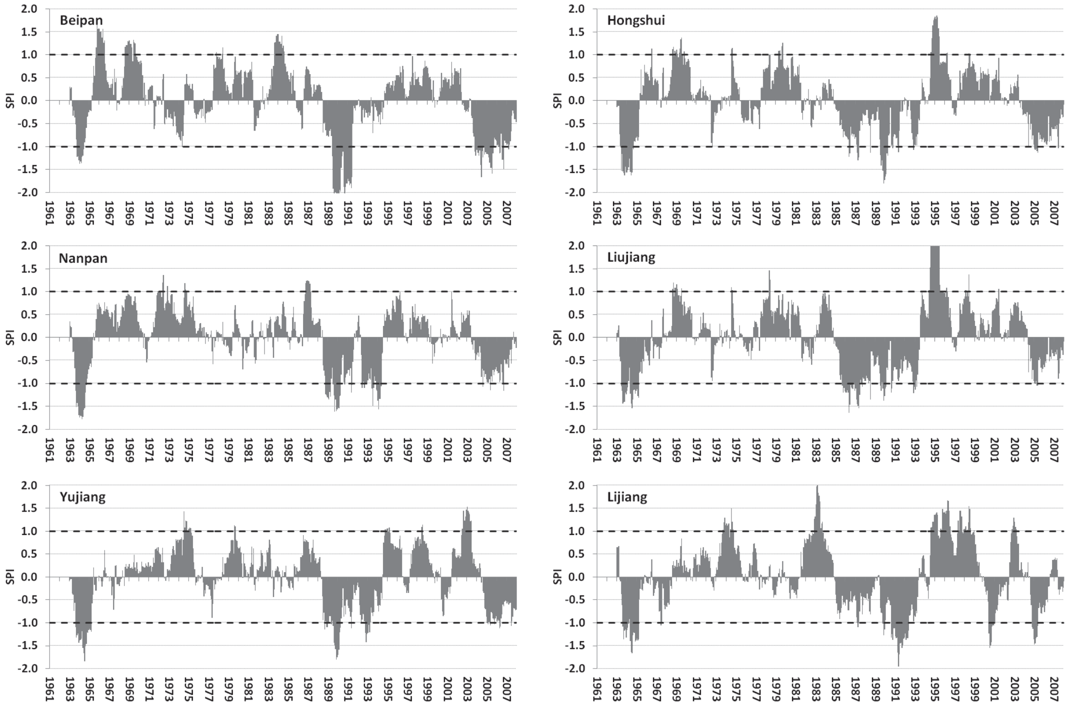

Fig. 6. SPI-24 of the six sub-basins in the Xijiang River Basin.

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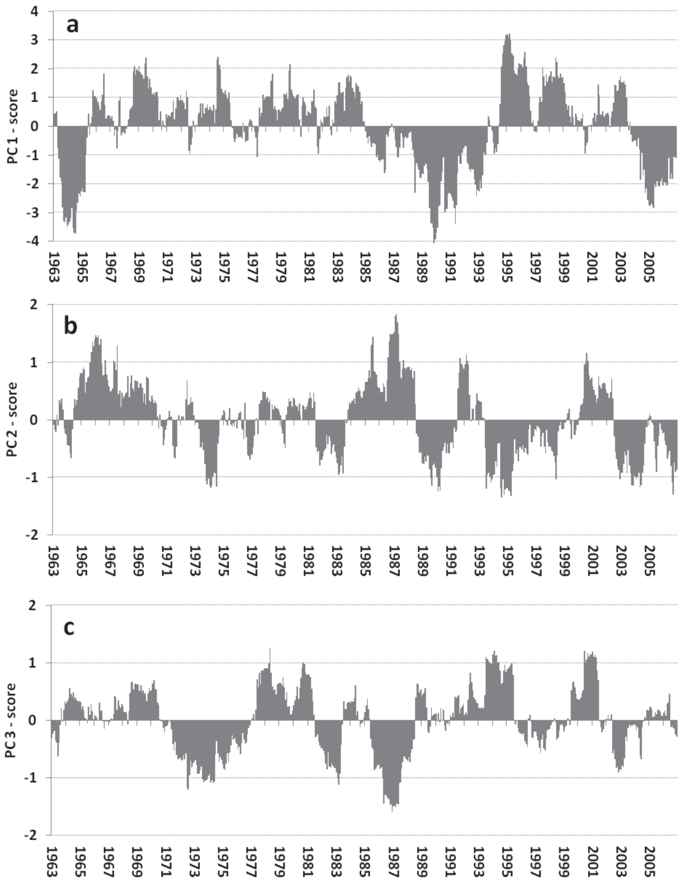

Fig. 7. PC scores of the SPI-24 in the Xijiang River Basin.

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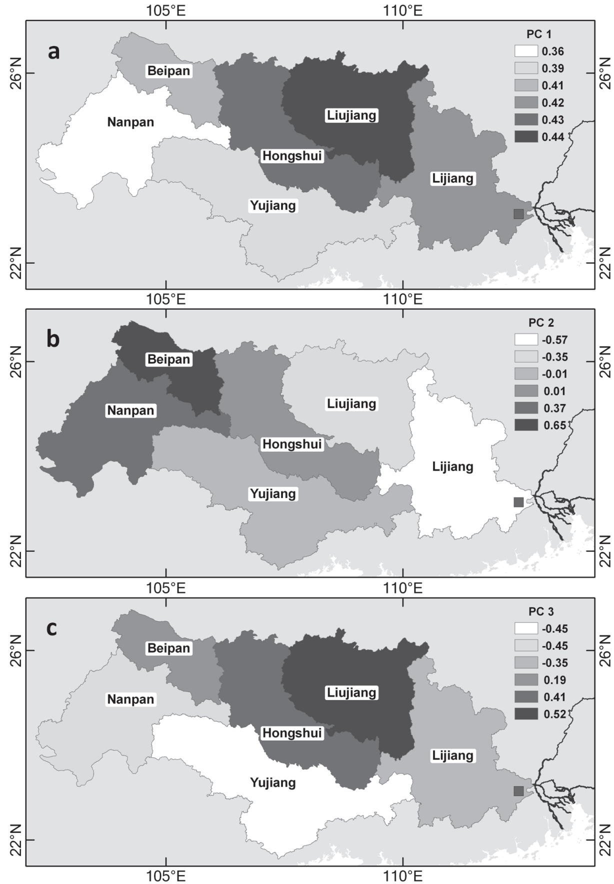

Fig. 8. Loading pattern of PC-1 **(a)**, PC-2 **(b)**, and PC-3 **(c)** in the six sub-basins of the Xijiang River Basin.

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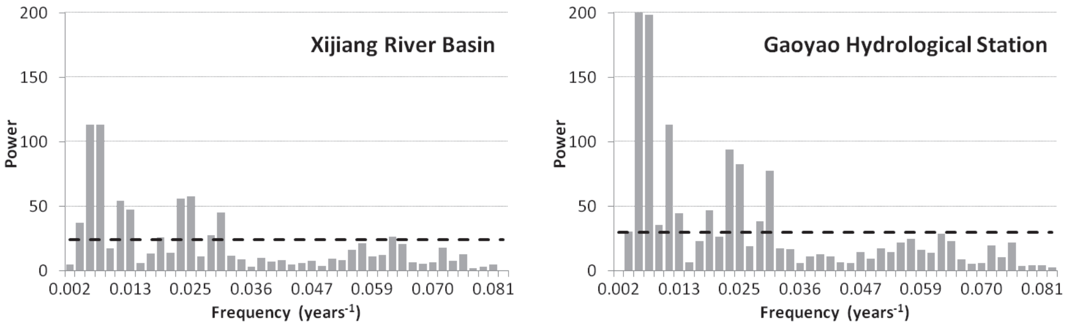

Fig. 9. Spectral analysis of the SPI-24 (left panel) and SDI-24 (right panel).

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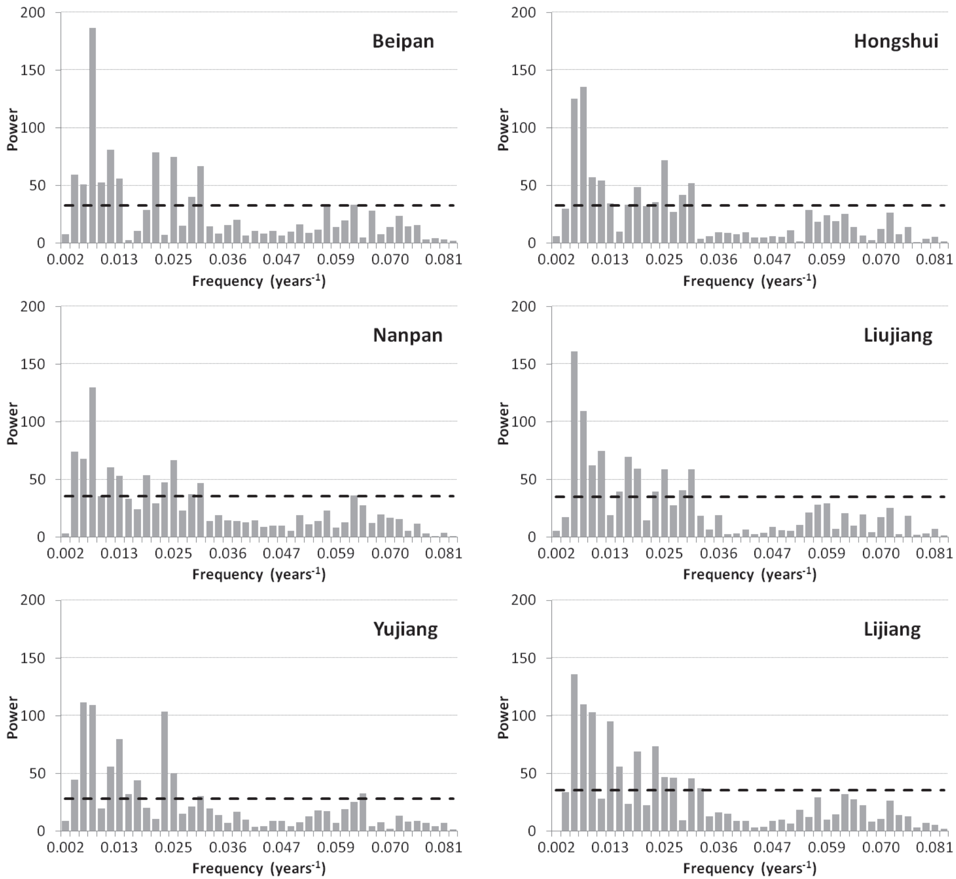

Fig. 10. Spectral analysis of the SPI-24 of the six sub-basins in the Xijiang River Basin.

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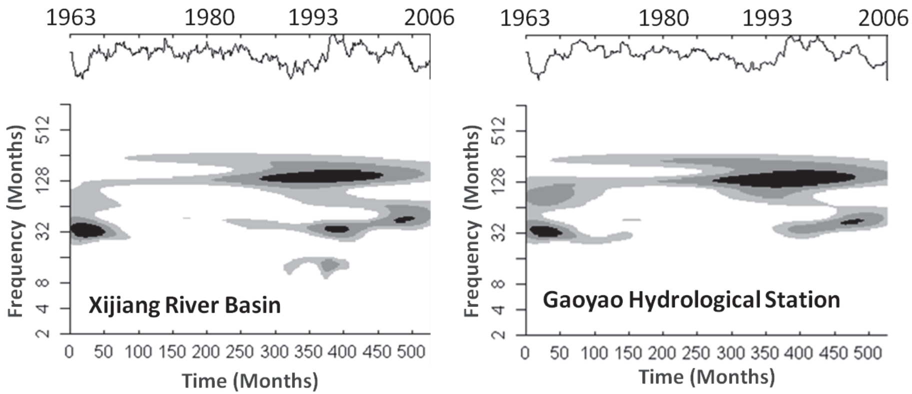

Fig. 11. Wavelet analysis of the SPI-24 (left panel) and the SDI-24 (right panel).

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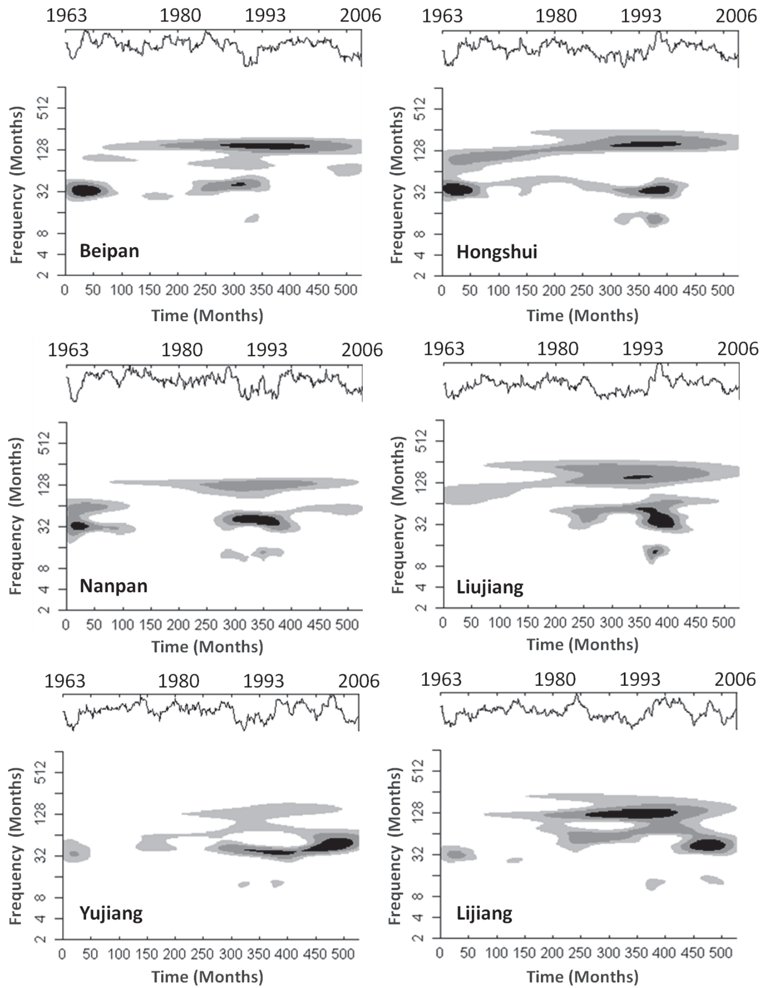

Fig. 12. Wavelet analysis of the SPI-24 of the six sub-basins in the Xijiang River Basin.

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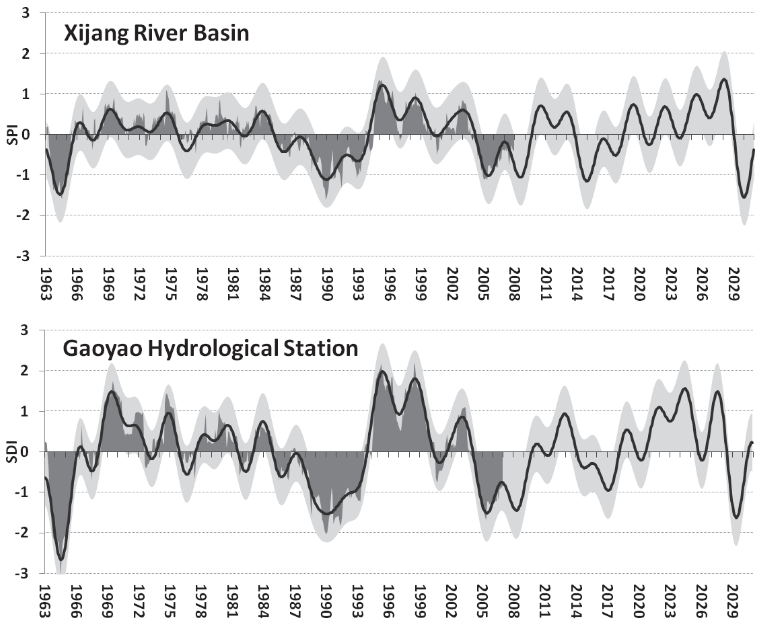

Fig. 13. Observed (dark gray shadings) and reconstructed time series (black line; confidence interval = light gray shading) plus extrapolation (starting in 2007) of the SPI-24 (upper panel) and SDI-24 (lower panel) 1963–2030.

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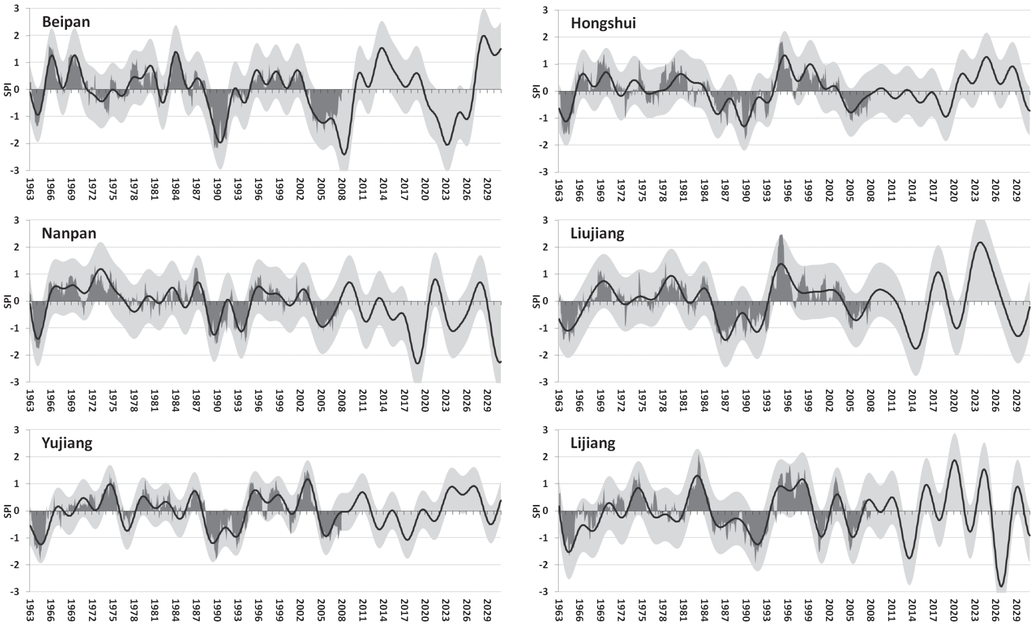

Fig. 14. Observed (dark gray shadings) and reconstructed time series (black line; confidence interval = light gray shading) plus extrapolation (starting in 2007) of the SPI-24 of the six sub-basins in the Xijiang River Basin 1963–2030.

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