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Paleoclimatological perspective on the hydrometeorology of the Mekong Basin

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Abstract

During recent decades the Mekong River has experienced substantial interannual variations between droughts and major floods. The causes of these variations have been sought in climate change and dam construction. However, so far little research has addressed whether these recent variations are significantly different to long-term variations in the past. Hence, the aim of our paper is to place the recent variations between droughts and floods into a historical and paleoclimatological context. To achieve this we analysed the Mekong's meteorological conditions over the period 1300–2005 with a basin scale approach by using the Monsoon Asia Drought Atlas (MADA), which is a Palmer Drought Severity Index (PDSI) dataset derived from tree-ring growth records. The correlation analyses, both in time and frequency domains, showed correlation between MADA and the Mekong's discharge over the period 1910–2005 which suggests that MADA can be used as proxy for the hydrometeorology of the Mekong Basin. We found that the meteorological conditions of the Mekong varied at multi-annual, decadal and centennial scales over the study period. We found two especially distinct features: firstly, multi-annual and decadal variation between prolonged wet and dry epochs; and secondly, epochs with higher or lower interannual variability between very dry and wet years. Furthermore we found two epochs with exceptionally large interannual variability, one at the beginning of 17th century and the other in the post 1950 epoch. Both epochs are characterized by distinct increases in variability between very wet and dry years. The variability in the post 1950 epoch is much higher compared to any of the other epochs included in this study. Thus, during recent decades the climate in the Mekong has exhibited features that have not been experienced for at least several centuries. These findings call for further climate research, particularly regarding increased climate variability, and resilient adaptation and development approaches in the basin.

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1 Introduction

Globally, the last decade has been a decade of extreme weather events, with record breaking events being observed in many regions of the world (Coumou and Rahmstorf, 2012). The Mekong River Basin has been no exception: in the 2010 dry season the Mekong River experienced record low water levels (MRC, 2011b), and in 2002 and 2011 record high floods were experienced (MRC, 2011a). Moreover, other severe droughts in the Mekong were observed in 1992, 1993, 1998, 1999, 2003–2005 (Te, 2007), and large floods in 2000, 2001, 2008 (MRC, 2010). The general perception is that the flood variability has increased, and explanations have been sought in climate change and dam construction (see, e.g. Qiu, 2010; Stone, 2010).

Floods and droughts play a major role in the Mekong Basin, as many of the region's economic activities and the livelihoods of its inhabitants are based on agriculture and aquatic ecosystems. Both of these are known to be affected by variations in hydrometeorological conditions (MRC, 2010; Baran and Myschowoda, 2009; Chinvanno et al., 2008). The annual flood pulse is a factor of key importance for aquatic ecosystem productivity, and it has been estimated that the economic value of flooding is US $ 8–10 billion per year (MRC, 2010). However, major floods can also be harmful, such as the flood in 2000 when more than 800 lives were lost, 2.4 million hectares of agricultural crops were damaged, and the economic losses were estimated to be US $ 460 million (MRC, 2010). Droughts are also harmful in the Mekong Basin, as they negatively affect agriculture, which is the single most important economic activity in the region (MRC, 2010). For example, the most recent drought of 2004–2005 affected all riparian countries and led to decreased agricultural production and fish catches, and subsequently to food and water shortages and indirect economic losses (MRC, 2010).

Recent research lends support to the general perception that the variability of Mekong discharge has increased and that the increase is largely climate-driven. Delgado et al. (2010) found that the likelihood of extreme floods increased during the last half of 20th century, whilst the probability of average floods decreased. They also

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found that the variability of annual maximum flows increased during the last quarter of the 20th century. The increase in variability has been linked to changes in the Western North Pacific Monsoon (WNPM) (Delgado et al., 2012), which has become more variable since the late 1970s (Wang et al., 2001). The WNPM is coupled with El Niño – Southern Oscillation (ENSO) (Wang et al., 2008), the magnitude and periodicity of which have increased since the late 1970s (Wang et al., 2008).

Although there are clear indications of a recent increase in hydrological variability in the Mekong, there is no comprehensive understanding of whether this recent variability falls within the normal long-term range. Therefore, a long-term (i.e. several centuries) comparison is needed. In mainland Southeast Asia there are a few studies focusing on long-term climate variability (Buckley et al., 2007; Fan et al., 2008; Sano et al., 2009; Buckley et al., 2010; Fang et al., 2010; Cook et al., 2010). These studies, except the study by Buckley et al. (2007), are based on a methodology where tree-ring chronologies are used to reconstruct past climates using the Palmer Drought Severity Index (PDSI) from a gridded PDSI dataset (Dai et al., 2004). The study by Buckley et al. (2007) did not use PDSI in the reconstruction, and focused mainly on interpreting the tree-ring chronology.

The studies listed above cover different geographical regions and varying time periods: Buckley et al. (2007) focused on North-Western Thailand over the period 1600 to 2005; Fan et al. (2008) focused on Yunnan in China over the period 1655 to 2005; Sano et al. (2009) focused on a region covering Northern Laos and Northern Thailand over the periods 1470 to 2005; Buckley et al. (2010) focused on a region covering most of Cambodia, Southern Laos, and Southern Vietnam over the period 1250 to 2008; Fang et al. (2010) focused on Yunnan in China over the period 1440 to 2007; and Cook et al. (2010) focused on the whole of Monsoon Asia over the period 1300 to 2005. The common finding of these studies is that of multi-year or decadal scale variations in climate. For example, Buckley et al. (2010) reported decades long droughts interspersed with intense monsoons in the 14th and 15th centuries that, they argue, contributed to the demise of the ancient Khmer capital, Angkor, in present-day Cambodia. Cook

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et al. (2010) reported the spatial extents of well known historical droughts in Monsoon Asia, such as the Strange Parallels Drought during the years 1756–1768 and the Great Drought during the years 1876–1878. Altogether, these studies show that the climate of mainland Southeast Asia has exhibited non-stationary behaviour and that there have been epochs with drier or wetter conditions compared to average.

While these studies have focused on the paleoclimatology of mainland Southeast Asia, there are no studies in the region that have used a paleoclimatological approach on a river basin scale coupled with discharge analysis, or that have examined the characteristics of hydrometeorological variation in recent decades in a longer historical or paleoclimatological context. The analysis of the paleoclimatology of large river basins using the long-term PDSI data based on tree-ring chronologies could significantly increase our understanding of long climate fluctuations and their impacts on hydrometeorological conditions. For example, in the Mekong Basin there are large uncertainties in the direction of future climate change impacts (Lauri et al., 2012; Kingston et al., 2011; Hoanh et al., 2010; Västilä et al., 2010; Eastham et al., 2008), and the issue of increased variability has not been adequately investigated. The climate change studies in the basin generally agree that temperatures will increase, and that rainfall may increase, but the direction of changes in discharge remains uncertain (Kingston et al., 2011; Lauri et al., 2012). Long-term analyses may increase our understanding of how the Mekong's hydrometeorology was affected by past changes in climate, and therefore provide valuable information on how future climate change may impact the region's hydrometeorology.

In this paper we have two main aims: (i) to examine how well the data from MADA describe the measured discharge of the Mekong over the period 1910–2005, and (ii) to examine the hydrometeorological characteristics (i.e. meteorological dryness and wetness and discharge) of the Mekong Basin in a paleoclimatological context over the period 1300–2005. We further examine whether the increase in flood and drought variability of recent decades falls within the normal long-term range. We achieve this by using the PDSI from the Monsoon Asia Drought Atlas (MADA), developed by Cook et al. (2010). For these purposes we calculated basin averaged PDSI for the Mekong and examined it with various statistical and signal processing methods and also compared it with measured discharge.

2 The Mekong Basin

The Mekong River Basin is the largest basin in Southeast Asia. It originates from the high elevations of the Tibetan Plateau and flows approximately 4800 km before discharging its waters into the South China Sea (MRC, 2005) (Fig. 1).The land area of the basin is 795 000 km^2, and is shared by China (21 % of total land area), Myanmar (3 %), Thailand (23 %), Lao PDR (25 %), Cambodia (20 %) and Vietnam (8 %) (MRC, 2005).

The climate of the Mekong is characterized by wet and dry seasons generated by the southwest (May–October) and northeast monsoons (November–April) (MRC, 2005). The annual average rainfall of the Mekong Basin is approximately 1400 mm, ranging from 300 mm to 3000 mm between individual measurement stations (Räsänen and Kummu, 2012). The driest parts of the basin are in the far north in the Tibetan Plateau and the wettest parts are in the east close to the Annamite mountain range. The majority of the rainfall occurs during the months of the southwest monsoon, which leads to an annual hydrograph with a pulsing nature. Low flows are experienced in March–April (on average 1800 $m^3 s^{-1}$ at Stung Treng) and high flows in August–September (on average 41 000 $m^3 s^{-1}$ at Stung Treng) (Räsänen and Kummu, 2012). The annual average discharge of the Mekong is approximately 14 500 $m^3 s^{-1}$ or 475 $km^3 yr^{-1}$ (MRC, 2005).

The Mekong's hydrological regime, with its annual flood pulse, has created a river basin rich in biodiversity (Junk et al., 2006) and with highly productive aquatic ecosystems (Lamberts, 2008). These aquatic ecosystems support one of the world's richest inland fisheries (Baran and Myschowoda, 2009) and are the source of food for millions of people (Hortle, 2007). Intra-annual variation between wet and dry periods has also shaped the region's agriculture, which is the single most important livelihood in

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the Mekong Region (MRC, 2010). The region's food production and livelihoods have co-developed with the monsoon climate and are therefore susceptible to variations in it. For example, the timing, length, and magnitude of the monsoon season and flood pulse affect agricultural production (MRC, 2010; Chinvanno et al., 2008) as well as fish catches (Baran and Myschowoda, 2009).

The Mekong Basin is also undergoing rapid demographic change, and economic and technological development, which impose pressures on its natural resources, including water (Pech and Sunada, 2008). A major concern has been the impacts of hydropower development, as it is feared that this may negatively affect the productivity of aquatic ecosystems, and therefore livelihoods and food security in the region (Lamberts, 2008; Stone, 2011; Grumbine et al., 2012; Ziv et al., 2012; Dugan et al., 2010; Baran and Myschowoda, 2009; MRC, 2010; ICEM, 2010). The population in the Mekong Basin has grown from 63 million in 1995 to 72 million in 2005 (Pech and Sunada, 2008) and it has been estimated that the food demand in the region will double by the year 2050 (FAO, 2010).

3 Methodology

The analyses can be divided to two parts: (i) comparison between MADA and Mekong's discharge; and (ii) paleoclimatological analysis of the Mekong's hydrometeorological conditions over the period 1300–2005. Firstly, in the comparison of MADA and the Mekong's discharge we examined how well the basin wide approach with MADA reflects the measured discharge of the Mekong Basin. For this, we calculated basin averaged PDSI for the catchment area above the Stung Treng discharge measurement station (PDSI_{ST}) and compared this with the discharge measurements over the period 1910–2005. The comparison was carried out using visual examination, smoothing, moving window variance, spectral analysis, continuous wavelet transform (CWT), wavelet coherency (WTC), cross wavelet transform (XWT), and probability density functions (PDF).

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Secondly, in the paleoclimatological analysis of the Mekong's hydrometeorological conditions over the period 1300–2005, we calculated the basin averaged PDSI for the Mekong Basin ($PDSI_M$) from MADA (Cook et al., 2010). From $PDSI_M$ we then identified prolonged wet and dry epochs and examined the general characteristics of the Mekong's meteorology. For the identification of wet and dry epochs we used smoothing methods and visual examination of the time series, and for the examination of the general characteristics we used CWT and spectral analysis. The CWT was used to reveal temporal variations in $PDSI_M$ in the frequency domain and the spectral analysis was used to support the CWT analysis. The results from the spectral analysis are shown in the Supplement. Moving window variance was also used to support the historical analysis and visualize the epochs with high variations. Furthermore, we used General Extreme Value analysis (GEV) to examine the changes in the meteorological variability between different centuries. The data and methodologies used in all of the analyses are described in more detail in the following sections.

3.1 Data

The original PDSI data in MADA (Cook et al., 2010) were reconstructed using tree-ring records from more than 300 sites in Asia, together with a gridded PDSI dataset (Dai et al., 2004). The resulting MADA dataset is a seasonal gridded PDSI dataset for June-July-August monsoon months with a 2.5° spatial resolution, covering Monsoon Asia over the period 1300–2005. The method for reconstruction of the gridded dataset was based on a point by point regression method. PDSI is a widely used index for describing meteorological drought and wetness (Heim, 2002; Dai et al., 2004), and was originally developed by Palmer (1965). The PDSI is based on precipitation and temperature, which are used in the calculation of atmospheric moisture supply and departure at the soil surface. A major benefit of the PDSI in long-term climate and hydrometeorological analyses is that it is based on meteorological factors and thus reflects only the variations in climate excluding the potential influences of land use changes, dam construction, and irrigation, which may be contained for example in discharge data.

In general, MADA provides an important means for understanding climate in Monsoon Asia and it has already proven to be efficient for this purpose (Wahl and Morrill, 2010; Bell et al., 2011). The MADA was obtained from NOAA's paleoclimatology online database (NOAA, 2010).

For our analyses we used the MADA PDSI dataset to derive basin averaged PDSI for the entire Mekong Basin ($PDSI_M$) and for the part of the basin upstream from Stung Treng ($PDSI_{ST}$). Stung Treng is the most downstream discharge measurement station with long data coverage before the river enters to the Cambodian floodplains and Mekong Delta. $PDSI_M$ and $PDSI_{ST}$ were calculated as area weighted averages of the MADA PDSI grid cells that are fully or partly inside the specific catchment area (see location of used MADA grid cells in Fig. 1). This produced two time series (1300–2005) describing the monsoon conditions of summer months June-July-August of each year above.

Daily discharge data from Stung Treng were obtained from the Mekong River Commission's quality assured database (MRC, 2011c). The discharge data cover the period 1910–2005, but the period before 1952 is known to be less reliable (personal communication with Erland Jenssen, Mekong River Commission). This first part (1910–1952) of the time series is lacking a rating curve and the actual discharge has been calculated retrospectively with rating curves defined after the year 1952. Therefore, we expect that the first part of the time series is not accurate for analyses at an annual resolution, but sufficient for analysis of long-term patterns. For the final analyses the daily discharge data were transformed into cumulative flows of hydrological years, which were defined as the beginning of May to the end of April of the next year, following Kummu and Sarkkula (2008).

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3.2 Methods

3.2.1 Smoothing

We used two methods to smooth the data, the moving average and locally weighted regression (LOESS) (Cleveland, 1979; Cleveland and Devlin, 1988). For the moving average we used a 21-yr long window, which was moved forward in time steps of one year. LOESS is a model that uses multiple regression models to fit a function on the time series with an *n*-length subset of the time series data. By fitting the function on the original data, the result is a smoothed time series and the degree of smoothing depends on *n*. In this study we used $n = 21$ as it was found to remove adequately sub-decadal variation and reveal decadal scale patterns.

3.2.2 Identification of prolonged wet and dry epochs

The wet and dry epochs of multi-annual and decadal lengths were identified using both the original $PDSI_M$ data series and the LOESS smoothed series. Firstly, we defined thresholds for the annual and smoothed $PDSI_M$ data to mark the dry and wet epochs. For the annual data the years with values below −1 were defined as dry years and the years with values above 1 were defined as wet years. These thresholds correspond approximately to the 20 % lower (19.7 %) and upper (19.4 %) quantiles, respectively. The PDSI value −1 (+1) is commonly used to indicate the threshold for moderate drought (wet spell), but it is dependent on region specific standardization of the index (Alley, 1984). For the smoothed data the same percentages for upper and lower quantiles as for the annual data were used as thresholds to define dry and wet epochs. The respective dry epoch threshold for the smoothed data was −0.39 and the threshold for wet epoch was 0.35. Secondly, we defined a prolonged dry or wet epoch as one with a minimum duration of three consecutive years. Thus, all the years with $PDSI_M$ values below (above) −1 (1) in the annual data and below (above) −0.39 (0.35) in the smoothed data, with a minimum of three consecutive years, were defined as prolonged multi-annual and decadal dry (wet) epochs.

3.2.3 Spectral analysis

The spectral analysis estimates the spectral density (i.e. power spectrum) of the time series, which shows the time series characteristics in the frequency domain (Chatfield, 2004). Spectral density reveals recurring periodicities and their relative strength in the time series. The estimation of the spectrum was based on Fast Fourier Transform.

3.2.4 Continuous wavelet transform (CWT), wavelet coherency (WTC), and cross wavelet transform (XWT)

The CWT shows the recurring periodicities and their relative strength in the time series similarly to the spectral analysis, but it also shows the temporal localization of these periodicities (Torrence and Compo, 1998). The WTC shows the periodicities where two time series co-vary and also the temporal localization of this co-variation and their phase relationship. The XWT in turn shows the periodicities and their temporal localization where the both time series have high common power. The statistical significance of the variation, co-variation, and common power were tested against red noise with a 5 % significance level. The null-hypothesis for the significance test is that the data are normally distributed and can be sufficiently described with a first order autoregressive model (AR(1)). Therefore, the normality and AR(1) assumptions were examined using the Shapiro-Wilk test (Shapiro and Wilk, 1965) and partial autocorrelation plots with 5 % significance levels. These hypotheses are important for CWT and XWT but the WTC is less sensitive to them. The wavelet analyses were based on the Morlet wavelet function with standard parameterisation from the wavelet package developed by Grinsted et al. (2004). The wavelet analysis was also complemented with variance analysis with a 21-yr moving window. The moving variance analysis was performed similarly to moving average.

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3.2.5 Probability density function (PDF)

PDFs describes the relative likelihood of the variable to take a given value (Dingman, 2008), i.e. it describes the occurrence probability of an event with a certain magnitude. The PDFs used were of normal distribution, and their parameters (mean (μ) and standard deviation (σ)) were estimated with the method of moments (Dingman, 2008). The normality of the data was already confirmed in the wavelet analyses.

3.2.6 General Extreme Value (GEV) distribution and return periods

The GEV describes the occurrence probability of an event of certain magnitude, but focuses on extreme events. In analogy to the mean and standard deviation of the normal distribution, the GEV is defined by parameters describing the location of the centre, scale of spread, and upper tail of the distribution (Katz et al., 2005). The GEV analysis was performed for seven periods, each with a length of hundred years, starting from the year 1306 using a software package developed by Gilleland and Katz (2011). The standard implementation of the package focuses on the upper part, or maxima, of the data. Thus we fitted the GEV to the original $PDSI_M$ series to examine the extreme wet years. For extreme dry years we used the inverted form of the original time series (multiplied by -1), as suggested by Katz et al. (2005). This method produced return period plots for each century.

4 Results

First, in the results section we have presented the comparison of $PDSI_{ST}$ and discharge at Stung Treng where we examined how well the basin averaged PDSI describes the measured hydrology, namely the discharge, of the Mekong over the period 1910–2005. Second, we have presented the results from the analysis of $PDSI_M$ where we examined characteristics of $PDSI_M$ both in time and frequency domains. The results are presented in detail in the following sections.

4.1 The comparison of $PDSI_{ST}$ and discharge at Stung Treng

To explore how the PDSI represent hydrology in the Mekong, we compared the $PDSI_{ST}$ and discharge at Stung Treng over the period 1952–2005 (Fig. 2a), when discharge data were thought to be reliable for annual comparison (see Sect. 3.1). The annual values of $PDSI_{ST}$ and discharge show a significant correlation ($r = 0.55$, $p < 0.01$), although some differences exist. When $PDSI_{ST}$ and discharge were smoothed with LOESS and a moving average of 21-yr window over the period 1910–2005, both time series showed remarkably similar patterns (Fig. 2b). The period from the 1920s to the 1960s was wetter than average, and the period from the 1970s to the 1990s was drier than average. In general, the smoothing with the moving average increased the correlation between the two time series. The use of window sizes of 3, 5, 11, and 21 yr resulted in correlation coefficients (r) of 0.56, 0.62, 0.82 and 0.89 ($p < 0.01$ for all the window sizes), respectively between $PDSI_{ST}$ and discharge. Smoothing has tendency to increase correlation as the smoothing window size increases and, therefore, these correlations are only indicative. The moving variances with a 21-yr moving window show that the variance of $PDSI_{ST}$ and discharge follow similar patterns, and that the variances have increased during the 1910–2005 period (Fig. 2c), the trend being significant (trend test with linear regression, p for slope coefficients < 0.01). The correlation between moving variances is 0.73 ($p < 0.01$). The fitted PDFs of $PDSI_{ST}$ and discharge from the periods 1910–1960 and 1961–2005 (Fig. 2d) indicate that the variances have increased in both parameters (standard deviation, σ, approximately doubled from the first period to the second one). The results also indicate that the first period was wetter than the second period ($\mu > 0$ for the first period and $\mu < 0$ for the second one). The PDFs clearly point out that the probability of very wet and dry years was higher during the second period.

The CWT and spectral analysis of $PDSI_{ST}$ and discharge over the period 1910–2005 show that both variables have recurring periodicities with wavelengths of 4–6, 10–14, and 19–30 yr (Fig. 3a, b; S1 in the Supplement). The periodicity of 4–6 yr was stronger

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both in $PDSI_{ST}$ and discharge during the 1910s–1930s, 1950s–1970s, and from the 1980s onwards, while the periodicity of 10–14 yr was strongest between the 1930s and 1960s. The periodicity of 20–30 yr was strong for most of the 20th century. The majority of the results for this particular periodicity are, however, outside the cone of influence of the wavelet analysis, and therefore should not be considered. The wavelet analysis shows a remarkable increase in periodicities of 2–7 yr for both $PDSI_{ST}$ and discharge in the post 1950 period (Fig. 3a, b). The statistically significant areas for discharge (areas marked with black line in Fig. 3a) are not entirely reliable as the partial autocorrelation plot showed a significant peak at lag 5 suggesting the discharge to be AR(5) process, which is against the basic assumptions of the significance testing.

The WTC of $PDSI_{ST}$ and discharge confirms that the two time series co-vary in multiple frequencies (Fig. 3c). Strong co-variation can be observed in WTC at wavelengths of 4–6, 10–14, and 19–30 yr (Fig. 3c); this is also observed in the CWT analysis (Fig. 3a, b). The XWT in Fig. 3d shows that both time series have common power at these same wavelengths, but more strongly at wavelengths of 4–6 yr. Both the WTC and the XWT confirm the increase of periodicities below wavelengths of 4 yr from 1970s onwards. The phase arrows in the WTC and the XWT indicate that the $PDSI_{ST}$ and discharge have generally been more in phase with each other from the 1950s onwards, especially at wavelengths of 4–6 and 19–30 yr. The phase arrows also show that the discharge led the $PDSI_{ST}$ in the 1920s at wavelengths of 4–6 yr, while the $PDSI_{ST}$ led discharge in the 1930s–1960s at wavelengths of 10–14 yr. The reliability of the statistically significant areas of XWT (Fig. 3d) is also questionable because of the nature of the AR process of discharge.

4.2 The $PDSI_M$ for the Mekong Basin

As shown in the previous section, a strong correlation was found between PDSI and Mekong discharge. Therefore, the $PDSI_M$ is expected to be a good proxy for the basin's hydrometeorology for the period 1300–2005. The $PDSI_M$ for that period shows clear epochal patterns in the Mekong's hydrometeorology (Fig. 4a). The average conditions in hydrology varied between wetter and drier epochs at multi-annual and decadal scales. The most distinguishable dry and wet epochs are listed in Table 1 and are also shown in Fig. 6 in the discussion section. The recent dry epoch of 1977–1995 and the wet epoch of 1937–1956 were the driest and wettest epochs in the whole 1300–2005 period.

The 20th century shows a large number of very wet and dry years which can be seen from Table 1 and Fig. 4a. The large number of very dry years in the 20th and early 21st century (8 out of 10 record years occurred during last 50 yr of our study period) suggests that the last 50 yr have experienced remarkable increase in dry years. Although the wet years seem to be more scattered over the study period, it is notable that the two wettest years occurred during the last decade of the study period and five out of ten within the last 50 yr of the study period. Figure 4a also shows the years with $PDSI_{ST}$ values higher than 2 and lower than −2, which are generally used to indicate thresholds for severe drought and wet spells (Alley, 1984). These findings indicate that the frequency of very dry and very wet years has increased towards the end of our study period.

The CWT (Fig. 4b) and the spectral analysis (Fig. S2 in the Supplement) of the $PDSI_M$ also reveal highly volatile features in the Mekong's hydrometeorology. Five different epochs can be identified. First is the 1300–1575 epoch, which has relatively low variability but dominant periodicities with wavelengths of above 50 yr. The second epoch, 1575–1680, has dominant periodicities with wavelengths of 15–38 yr and also wavelengths of 4–6 yr. The third epoch, 1680–1780, is characterized again by dominant periodicities above 50 yr. The fourth epoch, 1780–1900, is characterized by dominant periodicities in wavelengths of 4–7. The fifth and last epoch, 1900–2005, is characterised by dominant periodicities in wavelengths of 4–5, 11–15, and above 50 yr. The second half of the fifth epoch clearly stands out from the whole study period 1300–2005 with high variability at multiple wavelengths. The spectral analysis (Fig. S2 in the Supplement) also shows that the power spectrum has the highest values in the fifth epoch, indicating that the variability has also been the strongest during the period 1900–2005.

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Although the differences in variability between the five epochs can be reliably observed from the CWT (Fig. 4b), their statistical significance test proved to be insufficient as the $PDSI_M$ data were found to be closer to AR(2) process than AR(1). This is against the assumptions of the significance testing (see Sect. 3.2), and therefore the statistically significant areas in Fig. 4b should be treated as somewhat unreliable.

The moving window of variance confirms that the variability in meteorological conditions varied over the 1300–2005 period (Fig. 4c). The most distinct increases in variability can be observed during the 1575–1680 and 1900–2005 periods. The last period, 1900–2005, shows the highest levels of variability, particularly in the post 1950 period, which have not been observed in the rest of the period 1300–2005.

Similarly to the other analyses, the results of the GEV analysis indicate that the last century is hydrometeorologically different than the earlier ones (Fig. 5). For both wet (Fig. 5a) and dry years (Fig. 5b), the return periods of extremes are shorter and the amplitude of the extremes larger in the last century compared to the previous centuries. For example, a wet year with a 50-yr return period had a $PDSI_M$ value of 2.1 during the period 1306–1906, and 3.8 during the period 1906–2005, indicating an 80 % increase in the magnitude of the 50-yr return period event. However, the occurrences of positive (i.e. wet) extremes seem to have increased more than the occurrences of negative (i.e. dry) extremes. The difference is also clearly demonstrated by simple counts of years with $PDSI_M$ values above 2 and below −2, representing approximately the 5 % lower and upper quantiles, respectively. For the period 1306–1906, the number of such years was 39, while for the period 1906–2005 the number was 22.

5 Discussion

5.1 Comparison of $PDSI_{ST}$ and discharge

The comparison of $PDSI_{ST}$ and discharge at Stung Treng (see Sect. 4.1) suggests that the basin averaged PDSI from MADA (Cook et al., 2010) is a good proxy for

Mekong main river flows. The $PDSI_{ST}$ and the discharge show considerable similarities in annual and long-term patterns, variances, and occurrence probabilities (see Figs. 2 and 3). The smoothed data of $PDSI_{ST}$ described well the wet epoch from the 1920s to 1960s, and the dry epoch from the 1970s to 1990s, as well as the increase in variance towards the end of the study period of 1910–2005. It should be noted that the correlation is significantly higher for the smoothed data than for the annual data. The wavelet analyses also indicate a strong relationship between recurring periodicities in discharge and $PDSI_{ST}$. Thus our analyses (visual comparison and correlation analysis of annual and smoothed data) indicate that the $PDSI_{ST}$ is a more efficient proxy for the hydrological conditions on multi-annual and decadal scales than on an annual scale.

Dai et al. (1998, 2004) found that basin averaged PDSI is a good proxy for streamflow in their analyses of seven of the world's largest river basins. Dai et al. (2004) found correlations varying from 0.6 to 0.8 between basin-averaged PDSI and streamflow. Our correlation analysis of the $PDSI_{ST}$ and discharge reveals a slightly lower correlation coefficient of 0.55 for the period 1952–2005. However, this correlation is still quite strong, especially considering that the $PDSI_{ST}$ is a product of complex reconstruction and it describes only the monsoon conditions from June-July-August whereas the discharge time series is a cumulative discharge of the hydrological year (May–April). Although June, July and August are very important months in the Mekong's hydrology, September and October also contribute significantly to the annual discharge (MRC, 2005).

The wavelet analysis also revealed that both $PDSI_{ST}$ (Fig. 3b) and discharge (Fig. 3a) show clear ENSO signals at wavelengths of 2–7 yr (Fig. 3b). This 2–7 yr periodicity is the well known occurrence interval for ENSO (Cane, 2005). The wavelet analysis revealed epochs with less variability at these same ENSO wavelengths, for example from the 1930s to the 1950s. This epoch of low variance corresponds well with known variations in ENSO-monsoon relationships (Wang et al., 2000; Torrence and Webster, 1999). The relationship between ENSO and the rainfall in the Mekong Region is documented in the literature (see, e.g. Juneng and Tangang, 2005; Räsänen and Kummu, 2012).

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The wavelet analysis also revealed phase shifts in the relationship between $PDSI_{ST}$ and discharge. The reasons for these shifts could not, however, be identified in this study. It is expected that the unreliability of the discharge data before the year 1952 may have contributed to differences in the relationship, as many of the phase differences were observed before the year 1952 (Fig. 3b, c).

5.2 $PDSI_M$ for the period 1300–2005

The $PDSI_M$ shows clear epochs of prolonged wet and dry epochs during the study period (Sect. 4.2). Similar epochs in mainland Southeast Asia have been reported by Buckley et al. (2007), Fan et al. (2008), Sano et al. (2009), Buckley et al. (2010), Fang et al. (2010), and Cook et al. (2010). The prolonged wet and dry epochs found in this study agree in many cases with the findings of the above research, but differences also exist (see Fig. 6).

The longest dry epochs, for which our study agrees with the results of earlier research, occurred around the 1340s–1360s, 1740s–1770s, 1860s–1900s, and 1960s–1990s, and the longest wet epochs, for which our study also agrees with the results of earlier research, occurred in the 1510s–1520s, 1590s, 1610s–1620s, 1710s–1730s, and 1930s–1950s (Fig. 6). Shorter but severe well-known drought epochs can also be observed from $PDSI_M$. These are, for example, the Strange Parallels Drought of 1756–1768 and the late Victorian Drought of 1887–1878 (Cook et al., 2010). The droughts associated with the known historical El Niño events of 1877–1878, 1888–1889 and 1918–1919 (Cook et al., 2010; Buckley et al., 2010) are also clearly visible in $PDSI_M$ (Fig. 4a).

Furthermore, Buckley et al. (2007) found that spectral analyses of the tree-ring chronology in Northern Thailand show significant variability at wavelengths of 2.2–4 and 48.5 yr. Fang et al. (2010) report similarly spectral peaks in the reconstructed PDSI from Yunnan at wavelengths of 2.3–5.5 yr, 20.2–40.9, and 56.8–60.2 yr. These recurring periodicities correspond with our findings of periodicities of 4–7, 15–38, and above 50 yr (Fig. 4b).

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The comparisons above are only indicative, as the findings are not directly comparable. For example, our findings are for the whole of the Mekong Basin, whereas the above studies have been carried out at smaller regional scales in different locations in mainland Southeast Asia (Buckley et al., 2007; Fan et al., 2008; Sano et al., 2009; Buckley et al., 2010; Fang et al., 2010) or at the larger continental scale of the Monsoon Asia Region (Cook et al., 2010). Furthermore, some of the above studies only focused on selected dry and wet epochs, used different months for PDSI reconstruction, or identified the dry and wet epochs differently.

5.3 Recent hydrometeorological events and trends in the Mekong

In recent decades the Mekong has experienced a large number of drought and flood years, for example, significant droughts were experienced in 1992, 1993, 1998, 1999, and 2003–2005 (Te, 2007). The $PDSI_M$ also indicates most of these years as being exceptionally dry. The years 1992, 1993, 1998, 2003, and 2005 ranked as the 1st, 2nd, 5th, 52nd, and 4th driest years, respectively of the whole period 1300–2005. In general, a large number of very dry years in the observed record occurred after 1950 (Fig. 4a). According to $PDSI_M$, eight of the ten driest years during the period 1300–2005 occurred after 1950. Similarly high occurrences of years with drought cannot be observed in other time-slices of the analysed $PDSI_M$ record, although occurrences in the early 17th century were relatively common. For example, the early 17th century experienced a few exceptionally dry years, namely 1629, 1634, and 1635, which rank as the 14th, 3rd and 9th driest years, respectively of the 1300–2005 period. These years coincide with the Little Ice Age, when many regions in Eastern Asia experienced anomalously cold temperatures (Jones and Mann, 2004).

As well as droughts, the post 1950 period has also experienced significant floods, such as those in 2000, 2001, and 2002 (MRC, 2010). According to $PDSI_M$, the 2000 and 2001 floods rank as the 1st and 2nd wettest years of the period 1300–2005, while the year 2002 was close to an average year. Altogether, the post 1900 period experienced six of the ten wettest years of the whole 1300–2005 period, according to $PDSI_M$.

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Our results, including moving variances (Fig. 2b), probability density functions (Fig. 2c), continuous wavelet transform, and spectral analysis of the $PDSI_M$ (Fig. 4b and Fig. S1 in the Supplement) and $PDSI_{ST}$ (Fig. 3b and Fig. S2 in the Supplement) and the GEV (Fig. 5), indicate that the hydrological variability in the Mekong has increased during the last century, and more significantly in the post 1950 period. The most significant feature of the post 1950 period is the increase in periodicities of 2–7 and 11–15 yr; similarly strong short-term periodicities cannot be seen elsewhere in the period 1300–2005. The moving variance of $PDSI_M$ (Fig. 4c) illustrates the recent increase in hydrological variability very well. Our findings of increased variability strengthen the findings of Delgado et al. (2010). They examined the changes in variance of the Mekong's discharge and found that the variance in discharge has increased in the last quarter of the 20th century, and that extreme floods have become more common. Delgado et al. (2012) linked the increased variance to the enhanced variability in Pacific Sea surface temperatures, and especially to the Western North Pacific Monsoon.

5.4 Future research directions

There are several studies that have focused on the past and future climate of the Mekong Region. The most recent future climate change studies (Kingston et al., 2011; Lauri et al., 2012; Västilä et al., 2010; Hoanh et al., 2010; Eastham et al., 2008) suggest that average conditions in the Mekong will generally be warmer and that rainfall may increase. These studies did not, however, explicitly address possible changes in future climate variability although the issue is discussed in many of the articles. Several studies focusing on past climate (Buckley et al., 2007, 2010; Fan et al., 2008; Sano et al., 2009; Fang et al., 2010; Cook et al., 2010; Ward et al., 2007), as well as the present study, have focused on variability, and all conclude that the climate in mainland Southeast Asia is highly non-stationary and varies at multi-annual, decadal, and centennial scales. The most recent research findings (Delgado et al., 2010, 2012), including the findings of this study, strongly indicate that recent decades have exhibited

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remarkably high levels of climate and hydrometeorological variability in the Mekong Basin. Research related to the future climate and hydrometeorology of the Mekong still gives a fragmented picture, and there is a need for unifying research work to draw further conclusions on the direction of climate change impacts. For example, it is not clear whether the observed increase in the climate variability and occurrence of extreme events in the Mekong is due to global climate change. However, there is some evidence on the increase in extreme events in many regions of the world, especially in extreme precipitation events (Coumou and Rahmstorf, 2012; IPCC, 2012), but strong regional differences also exist (IPCC, 2012). One potential reason for increased climate variability in the Mekong region, which should be further investigated, are the changes in the Tropical Central Pacific sea surface temperatures (SST). The Tropical Pacific SST has become more responsive to extratropical atmosphere since 1990 which have resulted in more frequent El Niño Southern Oscillation (ENSO) events (Yu et al., 2012) and the Mekong region is known to be affected by ENSO (Juneng and Tangang, 2005; Ward et al., 2010; Räsänen and Kummu, 2012). Furthermore, climate change studies focusing on future climate projections could also address more broadly the issue of climate variability and extreme events, although it has been reported that the future climate projections made by climate models may underestimate extreme events (Allan and Soden, 2008).

A promising approach, as the results of this study suggest, would be to use hydrological models with paleoclimatic forcing data to simulate paleodischarges. Such an approach has been carried out in studies at the basin scale (Bogaart et al., 2003; Notebaert et al., 2011; Renssen et al., 2007; Ward et al., 2008, 2011) and for several large basins at the global scale (Aerts et al., 2006; Ward et al., 2007). The results of the latter suggest that the mean discharge of the Mekong was significantly higher than present during the Mid and Early Holocene. However, these studies have so far not addressed changes in variability in paleodischarge.

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6 Conclusions

In this paper our aim was to explore whether the reported increase in flood and drought variability of recent decades in the Mekong Basin falls within the normal long-term range. To achieve that, we used the basin averaged Palmer Drought Severity Index (PDSI) derived from the Monsoon Asia Drought Atlas (MADA) to study the hydrometeorological characteristics of the Mekong Basin in a paleoclimatological context over the study period 1300–2005. Furthermore, we examined how well the data from MADA correspond with the measured discharge of the Mekong.

We found that the basin-averaged PDSI derived from MADA is a good proxy for the discharge of the Mekong. Our results revealed that the Mekong's hydrometeorological conditions (i.e. meteorological dryness/wetness and discharge) have varied in multi-annual, decadal, and centennial scales during the study period. A distinct feature in the Mekong's hydrometeorological conditions was that they have varied between wetter and drier epochs with multi-annual and decadal lengths. Furthermore, five epochs with different characteristics were identified. The most recent epoch, from the year 1900 to year 2005, is the most distinct epoch of all, showing a significantly higher variability and occurrence of extreme dry and wet years than in any previous time-period studied, especially during the post 1950 period. For example, the period 1900–2005 contained eight of ten driest and five of ten wettest years of the whole study period.

Whether these recent changes in hydrometeorological variability originate from global climate change or natural changes in regional climate patterns could not be concluded. However, our findings provide valuable information for future climate studies in the Mekong Basin. The existing climate change studies show a great degree of uncertainty in the direction and magnitude of changes in Mekong's discharge. Furthermore, they focus mainly on changes in average conditions and not on changes in variability and extremes. Therefore, the results of our study provide information on recent hydrometeorological variability, extremes and related trends in paleoclimatological

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context, which complement the current knowledge derived from the climate change studies.

Our results suggest that the Mekong has experienced exceptional times during the recent decades in terms of increased climate variability. If the trend of increased climate variability continues, that would inevitably affect ecosystems and societal functions in the Mekong Region. For example, the productivity of aquatic ecosystems and agriculture is closely linked to hydrometeorological variability, and moreover, the design of existing infrastructure is based on past, observed, climate conditions. Therefore, further research is needed to draw a more comprehensive picture of the origin and direction of recent changes in climate variability and their potential consequences on ecosystems and societies.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/9/12729/2012/hessd-9-12729-2012-supplement.pdf.

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Table 1. Prolonged wet and dry epochs and ten driest and wettest years in the Mekong Basin according to basing averaged PDSI ($PDSI_M$) derived from Monsoon Asia drought Atlas (MADA).

	Range of years / individual years
Dry epochs	1325–1327, 1342–1367, 1401–1408, 1416–1424, 1478–1492, 1606–1611, 1629–1649, 1669–1683, 1754–1770, 1867–1872, 1890–1893, 1896–1903, 1918–1920 and 1977–1995
Driest years	1992, 1993, 1634, 2005, 1998, 1997, 1958, 1991, 1635, and 1983
Wet epochs	1373–1376, 1506–1521, 1551–1554, 1564–1571, 1585–1600, 1618–1627, 1655–1664, 1710–1736, 1779–1785, 1803–1812, 1828–1831, 1860–1862, 1915–1917, 1924–1933, 1937–1956 and 1999–2005
Wettest years	2000, 2001, 1375, 1861, 1967, 1511, 1730, 1999, 1971, and 1928

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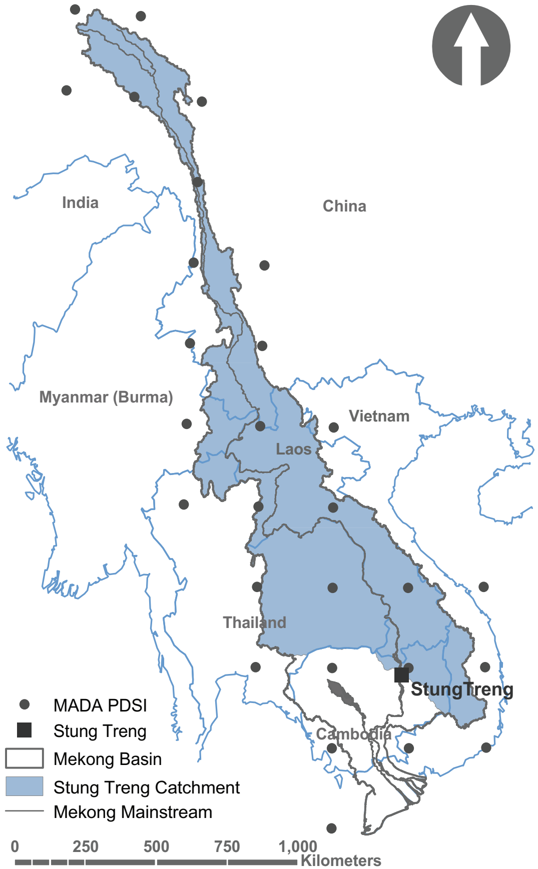

Fig. 1. The Mekong River Basin and the MADA PDSI grid cells (Cook et al., 2010) used in this study. The grid cells are shown with dots at the centre of the grid cells and the blue shaded area is the catchment area for the Stung Treng discharge measurement station.

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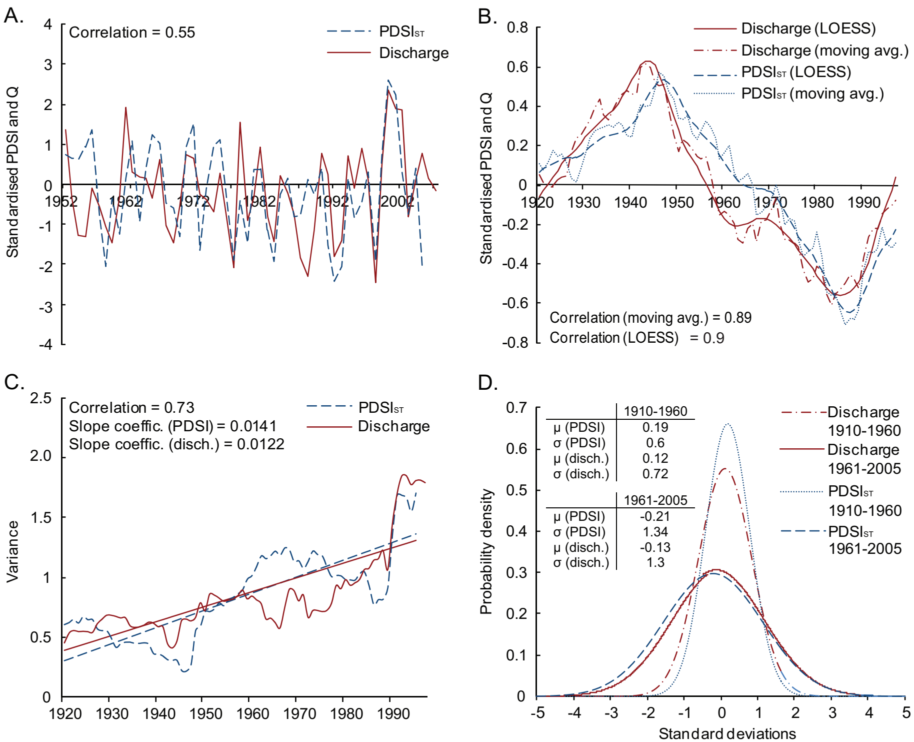

Fig. 2. Comparison of: **(A)** annual values; **(B)** smoothed values; **(C)** variances and their linear trends; and **(D)** fitted probability density functions (PDF) of $PDSI_{ST}$ and discharge over the periods 1910–1960 and 1961–2005. The linear trends of the variances are statistically significant (trend test with linear regression, p for slope coefficients < 0.01).

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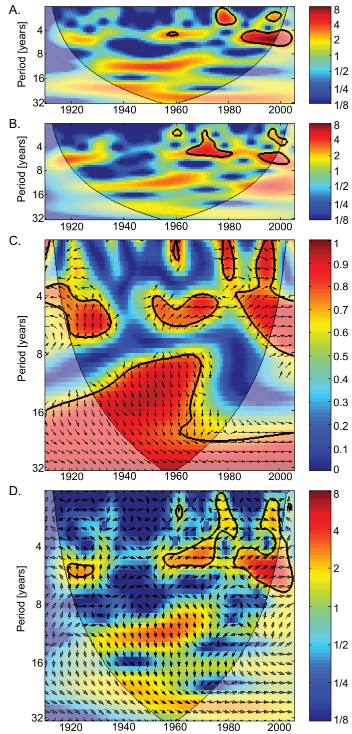

Fig. 3. Comparison of $PDSI_{ST}$ and discharge from the period 1910–2005 in frequency domain showing continuous wavelet transforms (CWT) for: **(A)** discharge; **(B)** $PDSI_{ST}$; **(C)** coherence wavelet transform (WTC) of $PDSI_{ST}$ and discharge; and **(D)** cross wavelet transform (XWT) of $PDSI_{ST}$ and discharge. In tiles **(A)**, **(B)**, and **(D)**, the increase in the power of the signal is shown in colour change from blue towards red and in tile **(C)** the colour change from blue towards red indicates increasing coherence between $PDSI_{ST}$ and Q_{ST}. Statistically significant (5 %) areas are marked with a black line. The arrows in tiles **(C)** and **(D)** show the phase angle between $PDSI_{ST}$ and discharge: → in phase; ←anti phase; ↑ discharge leading $PDSI_{ST}$ by 90° ; and ↓ $PDSI_{ST}$leading discharge by 90°.

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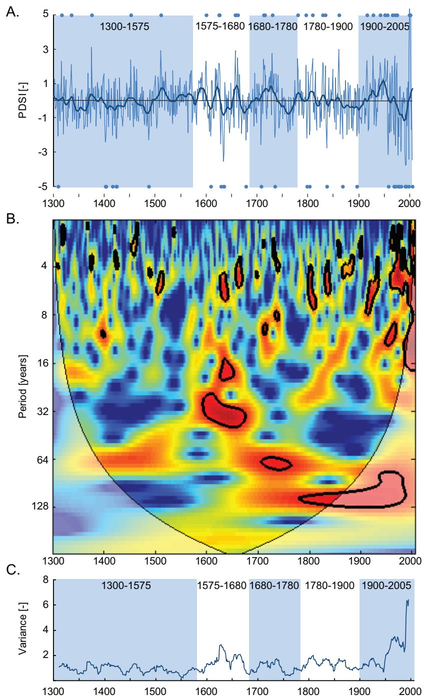

Fig. 4. The calculated: **(A)** basin averaged PDSI of the Mekong ($PDSI_M$) for the period 1300–2005; **(B)** continuous wavelet transform; and **(C)** moving variance of the $PDSI_M$. In tile **(A)**, the thin blue line represents annual values of $PDSI_M$, while the thick blue line represents the smoothing with LOESS; positive (negative) PDSIvalues refer to wet (dry) years. The dots in tile **(A)** represent the years when $PDSI_M$ values are larger than 2 or smaller than −2. In tile **(B)**, an increase in the power of the periodicities is marked with a colour change from blue to red, and periodicities which differ significantly (significance level 5 %) from red noise are marked with a black line. Five periods with different characteristics were also identified and are marked with light blue shadings in tiles **(A)** and **(B)**.

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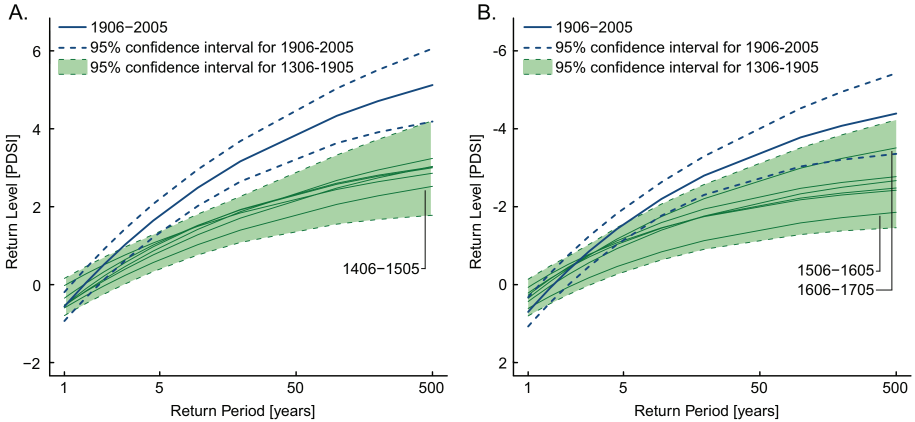

Fig. 5. The comparison of return periods of **(A)** wet years and **(B)** dry years: the dark blue continuous line is the return plot for the 1906–2005 period and the dark blue dashed line is its 95 % confidence interval; the green lines are return plots for 1306–1405, 1406–1505, 1506–1605, 1606–1705, 1706–1805 and 1806–1905 periods and the light green shaded is the area covered by their respective 95 % confidence intervals.

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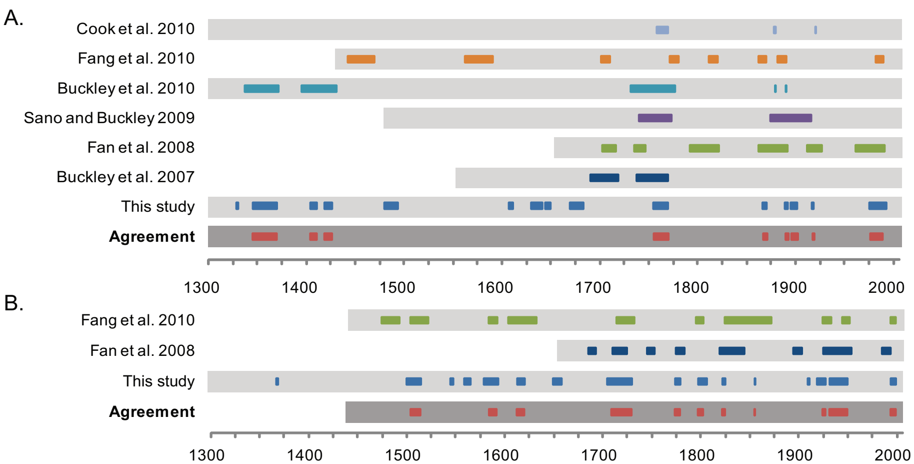

Fig. 6. Comparison of the **(A)** dry and **(B)** wet epochs found in this study to the findings of Buckley et al. (2007, 2010), Fan et al. (2008), Sano et al. (2009), Fang et al. (2010) and Cook et al. (2010). The grey area marks the study period of each study and "Agreement" refers to periods when one or more studies agree with ours on the occurrence of dry or wet epochs. The comparison is only indicative as the methods and spatial and temporal focus of the studies varies.

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