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# A climate-flood link for the lower Mekong River

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## Abstract

The Mekong River in Southeast Asia thanks its regular annual flood to the southwest monsoon. At longer time scales, the monsoon is a spatially and temporally variable circulation, with different annual to millennial variation for different regions. In this paper, the Indian and the Western Pacific component of the monsoon were analyzed to draw a light on the interannual flood variability of the Mekong River.

The focus is on the variance of flood season flows at 8 stations on the Mekong River, as well as on well-known climate indexes that reflect the dynamics of the monsoon circulation and ocean temperature anomalies. An effort was made to identify the temporal resolution that contains most of the interannual variability of both flood regime of the Mekong and monsoon intensity.

We found a close connection between the Western Pacific monsoon and the discharge in Kratie and other stations in the Southern Mekong region. In the frequency domain, the interannual to decadal variance of the Mekong discharge closely follows that of the Western Pacific monsoon. More importantly, the well-known regime shift of 1976 in the North Pacific is detectable in the frequency space for flood discharge and monsoon intensity. This suggests a relationship between Pacific sea surface temperature and monsoon variance, which is a good predictor for flood variance. This dependence influences the probability of occurrence of floods in the Mekong Delta.

## 1 Introduction

The Mekong in Southeast Asia, one of the world's major rivers, is dominated by the Asian monsoon in many aspects. Sectors like inland fisheries, navigation, hydropower and agriculture depend directly or indirectly in the intensity and temporal/spatial distribution of monsoon rainfall over the basin. They often conflict with each other (Grumbine and Xu, 2011; Bakker, 1999; Käkönen, 2008). The history of the region is also closely related to the variability of its climate, as it contributed to the birth and fall of civilizations (Cook et al., 2010; Buckley et al., 2010).

The link between monsoon intensity and the flood regime of the Mekong River is at the first sight a direct one. The clear division of the year between a dry and a wet season leaves no room for other main sources of precipitation in the region. Indeed, the monsoon months (approx. from May to October) account for 80 to 90 % of the discharge in the lower Mekong. Other sources are snow melt from the Tibetan Plateau and localized tropical storms, which are also related to the periodicity of monsoon circulation.

The importance of the monsoon to the peoples of South and Southeast Asia is not matched by our skill to predict the intensity or understand its variability (Shukla, 2007). The skill of modeling the mechanisms that force monsoon precipitation in the Asian-Pacific region is still moderate to poor over land masses (Wang, 2005). Making things more complicated, the Mekong River is located between two components of the monsoon. These are forced by two different oceans that condition the variability of the monsoon: the Indian and the Pacific Ocean. The northern part of the basin is dominated by the Indian component, called the Indian Monsoon (IM), and the southern part of the basin is dominated by the Pacific component, therefore called the Western North Pacific Monsoon (WNPM).

Although we divided the Asian monsoon in two different components according to different regional peculiarities, it has in its essence a common physical process. It is an Asian-wide disposition of the inter-tropical convergence zone (ITCZ) to exceptionally high latitudes during boreal Spring, due to ascending air over heated land masses, causing a high-level flow to comparably cooler areas over the ocean towards South (the Indian and the Western Pacific Oceans). This pressure gradient triggers surface level flows that evaporate water from the warm pools of the Western Indian Ocean (shores of East Africa, Arabian Sea and Red Sea) and Western Pacific. These flows finally generate convectional instability over the Asian continent and produce large amounts of rainfall.

On interannual time scales, the monsoon reacts to distinct mechanisms. Wang et al. (2001) showed that the East Asian, Indian and Western Pacific components have different patterns of interannual variability and geographical extent. This is mainly due to geographic boundary conditions of very different nature: the Indian Ocean is landbounded to the North and West, while the Western Pacific has a predominant East-West disposition of land and ocean. Additionally, the two components of the monsoon interact differently with El Niño/Southern Oscillation (ENSO) – both phenomena are coupled to the ENSO cycles, but the strength of the coupling has changed over time (Lau and Wang, 2006) – and with the Australian monsoon.

The Mekong River is located in a region affected by a mixed Indian and Western North-Pacific monsoon (Fig. 1). Precipitation from the IM is forced by the convective heat source over the Bay of Bengal, whereas precipitation from the WNPM is forced by the convective heat source over the South China Sea and the Southeast Asian Archipelagos. Wang et al. (2001) showed that in years of strong WNPM, the low level cross-equatorial jet west of Sumatra has a positive anomaly, contributing to the also positive anomaly of westward wind over the lower Mekong basin. The 2011 strong monsoon season over the lower Mekong basin and Southern Thailand has its origin in the mentioned positive WNPM anomaly (NCEP-CDAS, 2011).

The Mekong basin covers mainly tropical and sub-tropical latitudes with tropical monsoon in the south to humid continental climate in the north according to the Köppen classification (Peel et al., 2007). It is therefore to expect that the interannual variability patterns of streamflow are somehow distinct. Recently, Delgado et al. (2010) showed that a changing flood variability pattern could be identified along the river. Xue et al. (2011) related discharge in the frequency space with atmospheric circulation, revealing a spatial evolution of the power spectra in the basin.

There is a constraint in the time domain for the analysis of interannual variability: worldwide, the instrumental record of water level or discharge only exceptionally encompasses more than 100 yr of measurements (Kundzewicz et al., 2005). In the Mekong River, discharge has been recorded for almost one century. There are however other useful sources from proxy datasets like dendrochronoly (Cook et al., 2010), marine geology (Jian et al., 2001) and speleology (Zhang et al., 2008). These datasets are normally discrete in space and have different temporal extent and resolution. By combining them, the complete set of forcing mechanisms of the monsoon covering a wide range of frequencies is revealed. Namely, on geological time-scales, tectonics has the greatest effect; the Milankovich cycles (a model for earth harmonics) act on the millennial scale, as well as solar radiation (Clemens, 2006); sun spots have centennial to decadal variations (Schwabe-Hale cycles) (Wang et al., 2003); finally ENSO is responsible for interannual variability.

We intend to quantify changes in monsoon intensity and variability that affect the flood regime of the Mekong River. Further, we examine the linkages between the two monsoon components that affect the variability of floods in the region. We focus on the river flow upstream of the station of Kratie, i.e. excluding the Mekong Delta. Downstream of this point, the flood propagation follows a complex dynamics, due to topography (the delta system and the reversed flow of the Tonle Sap) and land use changes. The discharge downstream of this point is also significantly affected by tides, storm surges and sea level rise (Dung et al., 2011).

## 2 Data and methods

In this work we applied the continuous wavelet transform (CWT) for visually examining changes and enhancements in variability. The significance of these changes is later tested based on the discrete wavelet transform. The continuous wavelet transform is a time-frequency transformation of a time series. By convolving a function with certain properties with the data, it is possible to estimate the power of each frequency for the requested time and frequency resolution. A review of the methodology can be read in Torrence and Compo (1998) and Grinsted et al. (2004).

The discrete wavelet transform (DWT) is a special case of the continuous wavelet transform, where the frequency space is discrete and covers only diadic scales, i.e. scales equal to powers of 2. It has been shown that this transformation does not destroy the long-term memory of the data and that it effectively decomposes the variance of the time series into a number of chosen modes, which are related to a given frequency (Percival and Walden, 2000). The main advantage of the CWT over the DWT is its smoothing capacity and flexibility in the choice of frequencies for visualization purposes; however, the DWT is less redundant and therefore more used among the signal processing community.

The DWT was used to detect step changes in the variance of the flood discharge at different frequency levels. The time series of size $N$ is convolved with the wavelet filters to obtain the wavelet and scale coefficients. To calculate the wavelet variance as a function of time, the wavelet coefficients are not downsampled (as would happen in a standard DWT), but kept with size $N$. This is called a maximal overlap DWT and allows the direct estimation of the wavelet variance from the wavelet coefficients. The step change in variance can be detected by maximizing the ratio between the cumulative sum of squares and the sum of squares of the wavelet coefficients (Whitcher et al., 2002). Percival (1995) provides several ways of estimating the confidence interval (CI) of level $\alpha$ for the estimation of the wavelet variance; here the most conservative of them was used. If, for a given step change, the CIs of the variance before and after the change intersect, the step change cannot be considered statistically significant. Otherwise, the step change is statistically significant to the $1-\alpha$ level.

It is generally accepted that the distribution of geophysical data is skewed and must be transformed or handled accordingly. In this paper, we drew on previous knowledge about the data (Delgado et al., 2010; Dung, 2011) to conclude that the variables used are not normally distributed. For certain statistical tests, the mismatch between data and statistical model can lead to wrong confidence intervals. The data must be transformed whenever the methods used assume normally distributed data. We therefore standardized the hydrological and climatic data based on a 3 parameter lognormal distribution (parameterized as in Hosking and Wallis, 1997). The $Z$-scores obtained from this transformation were then used to produce all the results discussed in this paper.

Due to the strong annual cycle and the absence of floods outside the wet season, the study of the interannual variability of the flood regime of the Mekong can be performed based on annually resolved indicators that describe the severity of the flood season. Annual maximum discharge and flood season average discharge (considered as the June, July, August, September, October and November composite, i.e. JJASON) were our indicators of choice. The flood season was considered to last until November in order to include late flood peaks in the downstream stations, due to the superposition of upstream floodwave and typhoon landfall.

Both JJASON average discharge and annual maximum discharge were used in this study. The former is an important indicator of flood intensity in Southern Vietnam and Cambodia. A part of the flood volume is stored in the floodplains of Cambodia and in the lake Tonle Sap, but the remaining flows to inundate the Mekong delta. The duration of high water levels is critical for flood damage in the region and is mainly determined by the flood volume during JJASON. The annual maximum discharge, also used in this study, is necessary for any flood hazard assessment in the delta: Dung (2011) utilized both annual maximum discharge and JJASON average discharge for generating synthetic hydrographs based on a nonstationary approach. In this study, both variables will be analyzed.

In Fig. 2 the JJASON discharge for the stations Kratie, Stung Treng, Pakse, Mukdahan, Thakhek and Vientiane on the Mekong River is shown. These are the longest available quality checked time series for the Mekong basin. The discharge data was received from the Mekong River Commission (MRC) and the Southern Institute for Water Resources Research (SIWRR). The shaded area represents the subdecadal variance estimated with the wavelet power spectrum. The time series were trimmed to common lengths to avoid inconsistencies due to possible extreme events at both ends of the time series.

Relevant climate indexes were used that describe Pacific sea surface temperature (SST), like the ENSO and the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and monsoon dynamics (WNPM index and IM index) (Wang et al., 2001). Some

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of these indexes have a seasonal expression: ENSO is normally anomalous around Christmas and the monsoon indexes are mostly relevant during the summer months. Others, like the PDO, remain longer on a given mode. For the WNPM, IM and ENSO, boreal summer and winter averages were used, while for the PDO the monthly time series were used.

## 3 Changes in flood variance

The justification for focusing on variance changes and inhomogeneity is twofold: firstly, concerning flood hazard, variability is more important than averages (Katz and Brown, 1992), for the fact that small changes in variance can alter the configuration of the tails of the frequency distribution and have a greater effect on the probability of extremes than a similar change in the mean; secondly, we learned from Delgado et al. (2010) that flood variance in the downstream reaches of the Mekong River has been changing over time in the last century, with consequences for flood hazard estimation.

Other studies, e.g., Campbell (2007); Xue et al. (2011), focused on trends in the mean, either by applying the Mann-Kendal test or by simple linear regression. Delgado et al. (2010) showed that: (a) generally, a downward trend in the mean of the annual maximum discharge is present at three stations of the Mekong River; (b) there is an upward trend in variance in the lower part of the Mekong basin and (c) the increase in variance outweighs the decrease in averages in what concerns the probability of an extreme event. These studies assumed a continuous variation either on averages or variance over time (by assuming a linear, polynomial or a rank-based continuous variation). This is appropriate for detection of change, but fails to describe the dynamics of the change, for which a more adaptive model is necessary. In the present study, the continuous wavelet was used to identify changes in variance. It offers a very flexible decomposition of a time series, allowing for time and frequency definition.

Time series of JJASON average discharge for the gauges with the longest records in the Mekong are given in Fig. 2. In the background of each panel, the average subdecadal variance computed from the wavelet power spectrum is shown. The average subdecadal variance is defined as the variance of all scales lower than 10 yr averaged over the frequency domain. For more details see Torrence and Compo (1998). Two main features in the data are evident: the first is the enhancement in variance after 1970 in the three downstream stations; the second is the earlier enhancement in variance (1960) in the three upstream stations. This indicates that a north-south spatial pattern in interannual variability within the basin exists.

To validate our observations, we scanned the JJASON average discharge for step changes, using a cumulative sum of squares. For the three downstream stations of Pakse, Stung Treng and Kratie, the step change occurred in 1976. For this year, a regime shift in the SST and sea level pressure of the extratropical Pacific Ocean has been detected by several authors (Kerr, 1992; Percival et al., 2001). This change is towards an enhanced variance in the 2 and 4 yr scales. Further upstream in Mukdahan, Thakhek and Vientiane, some changes are still significant, but occur earlier in time (1962, 1971 and 1967, respectively). The subdecadal variance in Fig. 2 indicates the same, with upstream stations suffering an increase in variance earlier. These results suggest (a) a nonstationary flood regime based on step changes and (b) a possible relationship of the flood regime with the Pacific Ocean regime shift. Applying the same method to the annual maximum discharge did not yield statistically significant results; neither was there a clear pattern in the location and direction of the step changes.

## 4 Changes in monsoon variance

The quantification of the variability of the Asian monsoon at the continental scale was mainly accomplished within the last two decades (Wang et al., 2001). Before that, studies focused mostly on the local/national scale. A simple way of quantifying and predicting the interannual variability of the Asian monsoon at a continental scale is to derive a measurable variable representative of the physical processes. Wang and Fan (1999) reviewed the most important measures of monsoon intensity. More recently, many authors used these indexes for different purposes, such has characterizing the monsoon variability (Goswami, 2006), evaluating and validating model predictions (Paeth et al., 2008; Cherchi and Navarra, 2003) or investigating trends in monsoon intensity (Chase et al., 2003).

We used separate indexes for the Indian summer monsoon (IM) and the Western North-Pacific Summer monsoon (WNPM) following results from Wang et al. (2001). The intensity of the monsoon is represented by the difference between 850 hPa zonal wind velocities averaged over defined regions during June, July, August and September of each year. For the IM, these regions are located between Somalia and Sri Lanka and in Northern India. For the WNPM, they comprise an area between Southern Indochina and Southern Philipinnes and Southern China and Southern East China Sea. These indexes can be seen in Fig. 4 together with their subdecadal variance, obtained following Torrence and Compo (1998). This range of variance encompasses significant scales of variability and is in phase with the discharge in the Mekong River, as we will see in the next section.

The most relevant features in Fig. 4 are a period of enhanced variance of the Indian monsoon in the 60s and 70s, and a similar but longer period of enhancement in the Western Pacific Summer monsoon during the last quarter of the 20th century. Equivalent results were also obtained with different methods by Wang et al. (2001). The reason for different periods of enhancement of the two indexes is the greater response of the Western Pacific monsoon to thermal conditions in the Pacific, of which ENSO plays a crucial role. Wang et al. (2003) have shown that El-Niño events tend to enhance the Western Pacific monsoon circulation to a greater extent than the Indian monsoon circulation. Another hypothesis proposed in this paper is the contribution of the extratropical Pacific SST, which can be described by the PDO on the interdecadal scale (see Sect. 6).

Although both components of the monsoon deliver great amounts of precipitation to the basin, they have a distinct spatial and temporal variability. The IM affects the whole of the basin, although with greater prevalence in the northern part. The rainfall over the southern part of the basin is affected by the general monsoon circulation, but it is forced mostly by the intensity of the Western Pacific circulation, including the coupling with the Australian monsoon. The moist air masses travel across the equator, turn to north-eastern directions (due to the Coriolis acceleration) and enter the Mekong region (McGregor and Nieuwolt, 1998). By then the flow has a strong zonal component (along the earth's parallels) therefore converging to the highlands along the Vietnamese border, which leads to intense orographic precipitation. Later in the season, typhoons develop and may make landfall on the coast of Vietnam, prolonging the flood season or contributing to the development of distinct flood peaks, besides the general seasonal high flow.

The Western Pacific circulation is responsible for forcing rainfall over the area that contributes most to the discharge in the Mekong delta. This region, identified in MRC (2005) as the subbasins draining to tributaries between Pakse and Kratie, has an area of about 13 % of the whole Mekong basin. It is, however, responsible for about 23 % of the flood volume in the delta. Enhancements in either the intensity of the circulation or in its interannual variance are thus likely to have consequences for the flood hazard.

## 5 Quantifying the relationship between monsoon and floods

Ideally, proving a cause-effect relationship between two phenomena would require either a controlled repetition of the experiment in a laboratory or modeling the underlying physical processes by means of mathematics. The former is impossible, due to the scale of the phenomenon. The latter is underway, but until present with inconclusive results. The correlation between monsoon and flood frequency can be however quantified statistically, by plotting the cross wavelet spectrum of annual maximum discharge and a monsoon index. If there is a consistent phase relationship between the two, it is likely that one of the monsoon components forces the interannual variability of floods in the Mekong. This is shown in Fig. 4, where the upper panel represents the cross wavelet spectrum and the middle panel represents the average subdecadal variance of (a) the WNPM index and (b) the IM index, together with the variance of the annual maximum discharge measured in Kratie.

As we see in Fig. 4, upper panel, the WNPM index and annual maximum discharge are significantly in phase between the periods of 8 to 12 yr. In this kind of plot, arrows show the angle between the two periodic signals (arrow to the right means 0 radian; thick black contours enclose times and frequencies with significant phase coherence). For shorter timespans, like in the first and last ten years of the timeseries, the phase agreement spans from periods of 2 to 12 yr. In contrast, the IM index hardly shows any frequency coherent regions with phase locking. Further, as seen in the middle panel, the variance of the WNPM index modulates approximately the variance of the annual maximum discharge at Kratie at subdecadal to decadal scales. The JJASON average discharge presents a weaker phase locking during the whole time domain, but the same enhanced periods during the first and last ten years of the time series. This means that for decades with greater variance there is a stronger correlation between both indexes (Delgado et al., 2011), supporting the hypothesis that the enhancements of variance are a key to understand the link between the monsoon and the Mekong flood regime.

To find out if the north-south spatial pattern described in Sect. 3 affects the correlation between the WNPM intensity and the JJASON average discharge, the *Pearson* correlation between the two variables is plotted for all stations in Fig. 5. The results reveal an increasing correlation from north to south, althought the best correlation is still lower than 0.6 (significant at the 99 % level downstream of Mukdahan). This corroborates the hypothesis of the Mekong basin being a transition zone between two different monsoon regions, which is also suggested by Wang (2002). It was not possible to correlate the IM index with discharge. The correlation levels were below 0.1, which reveals that the interannual variability of floods in the lower Mekong is not modulated by the Indian Ocean monsoon circulation.

The correlations found are not enough to create a regressive model of annual maximum discharge in the lower Mekong River. However, in the frequency domain, the link between the WNPMI and the annual maximum discharge is significant on the decadal scale, as seen in Fig. 4. Enhancements in the variance of both signals occur in the 1970s and remain for the rest of the 20th century. Other drivers for the enhancements in variance cannot be ruled out completely: Lacombe et al. (2010) showed that the massive deforestation in Southern Laos during the Vietnam War (caused by bombing between 1965 and 1973) was a driver for increasing runoff yields. Dam construction in the upper Mekong basin could have had important effects on the flood regime, although it is unlikely that they would have affected downstream stations like Kratie during the flood season (Lu and Siew, 2006), and moreover, dam construction would tend to decrease the variability of flood magnitude. New dams are already planned for the lower Mekong River (Grumbine and Xu, 2011). A conclusive process based study about the effects of these drivers in the Mekong flood regime is still necessary.

## 6 The influence of the Pacific Decadal Oscillation

The interdecadal variability of SSTs and pressure levels of the Eastern North Pacific, under certain phases of the SOI, are known to drive early monsoon precipitation in Southern China (Chan, 2005), being also a regulator of Asian summer climate. The Pacific Decadal Oscillation is an index that reflects the North Pacific variability: a positive (negative) phase of the PDO is felt as far as the South China Sea, when the local SST suffer a light negative (positive) anomaly (Krishnan and Sugi, 2003). It is also known for signaling periods of high and low rates of ENSO events occurrence (Krishnan and Sugi, 2003).

The mechanism suggested by Chan (2005), by which a combination of the PDO and ENSO modulates precipitation in Southern China during the monsoon months could not be found when using the WNPMI or discharge in the Mekong. The relationship in the case of the Mekong may be more complex, due to its location in a transition zone between two monsoon circulations (McGregor and Nieuwolt, 1998). We found, however, a relationship between the subdecadal variance of the WNPMI and the PDO intensity that has important consequences for flood hazard in the Mekong. In the second half of the 20th century, the WNPMI subdecadal variance enhancements followed closely the PDO (here a lowpass filter was applied to the PDO). This could mean that the regime shift introduced by the PDO may be also present in the monsoon. In fact, several authors have argued in favor of this monsoon shift. In previous sections, we showed that this shift is present not only in the monsoon index but also in the discharge time series of the Mekong. The shift disappears in the upstream part of the basin, confirming the hypothesis that the precipitation regime in this area is mostly dominated by circulation patterns other than the WNPM.

The influence of the PDO on the flood discharge of the Mekong can be seen in the agreement between shift in variance of discharge time series in the downstream part of the basin and the PDO shift of 1976 (Fig. 3). This is expectable as the connection between the WNPM and flood discharge grows towards south (Fig. 5). The hypothesis that a part of the discharge variability may be explained by a measurable large-scale climate index is a very useful result for estimating flood hazard. The relationship should be kept in mind in future investigations: a validation of this hypothesis is still necessary and could only be achieved with longer time series from proxy records and climate modeling.

## 7 Conclusions

This paper outlined the main aspects of the interannual variability of floods in the Mekong River. By locating and quantifying variance enhancements in the flood discharge time series, it was possible to relate flood variance with the interannual variability of the Western North Pacific monsoon. The variability of the Indian monsoon was found to have less influence on the interannual flood regime of the lower Mekong than its Western Pacific counterpart. The northern part of the basin is dominated by a surface level flow entering the basin through the Bay of Bengal forced by the Indian monsoon. The southern part is under the effect of the Western Pacific monsoon, receiving a moist surface level flow from the Indian Ocean and maritime continent that is forced by the adjacent Western Pacific circulation.

Additionally, the hypothesis that the Pacific Decadal Oscillation plays a role in enhancing the interannual variability of the WNPM was strengthened. During the last 50 yr of the 20th century, the WNPM has been more variable during warm phases of the PDO. Further model based investigations are necessary to clarify the phenomenon.

Changing variance in the severity of floods is a defining aspect of flood hazard in the lower Mekong (Delgado et al., 2010). By proving that a regime shift in flood variance took place in the past, we abandon the concept of stationarity in flood hazard assessment. A climate-driven nonstationary flood frequency model is therefore necessary, especially when the future development of flood hazard is to be estimated.

Longer measured time series are needed to better define the linkages between the Western Pacific monsoon and flood variability. In the absence of enough data, the method of choice is to model the physical processes and from long model runs to identify the interactions between the large scale processes. An alternative is to use available proxy datasets that represent past climates. Both directions will in the future certainly open new perspectives in the hydrology of this region.

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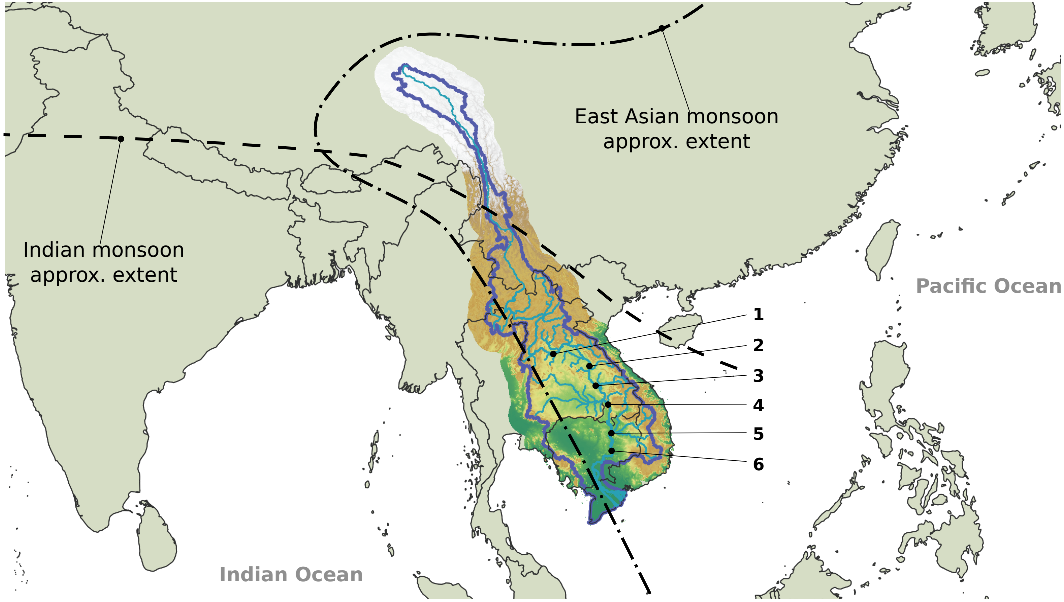

**Fig. 1.** Asian monsoon regions. Mekong River, its basin and the location of the gauging stations used in this study are shown. The approximate East Asia-Western North Pacific monsoon and Indian monsoon extents were taken from Holmes et al. (2009). The stations used in this study were Vientiane (1), Thakhek (2), Mukdahan (3), Pakse (4), Stung Treng (5) and Kratie (6).

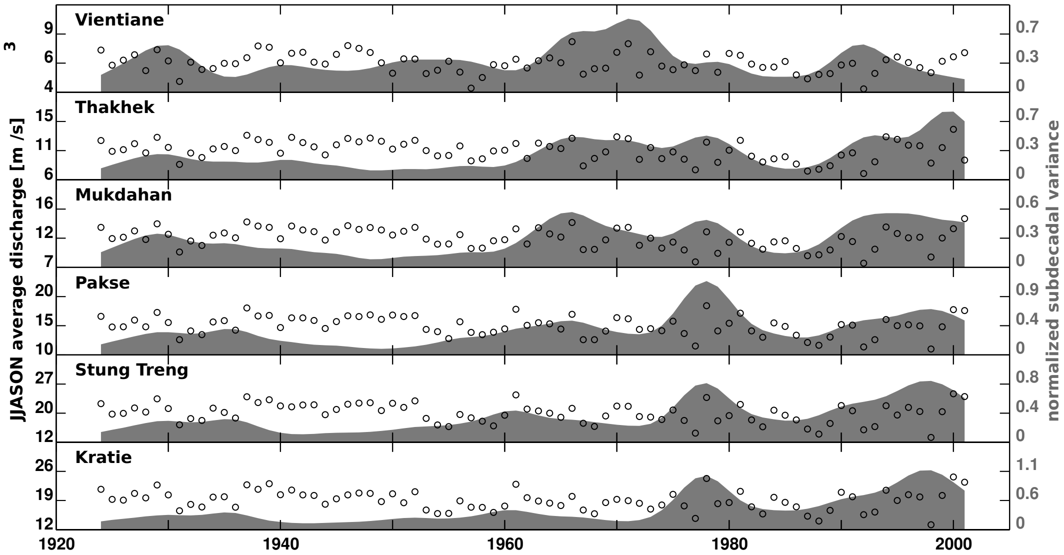

**Fig. 2.** Dots represent JJASON (June to November) discharge averages (left axis). The shaded areas show the subdecadal variability of the transformed discharge estimated with the Morlet wavelet (right axis). Lower stations show a later enhancement in variance.

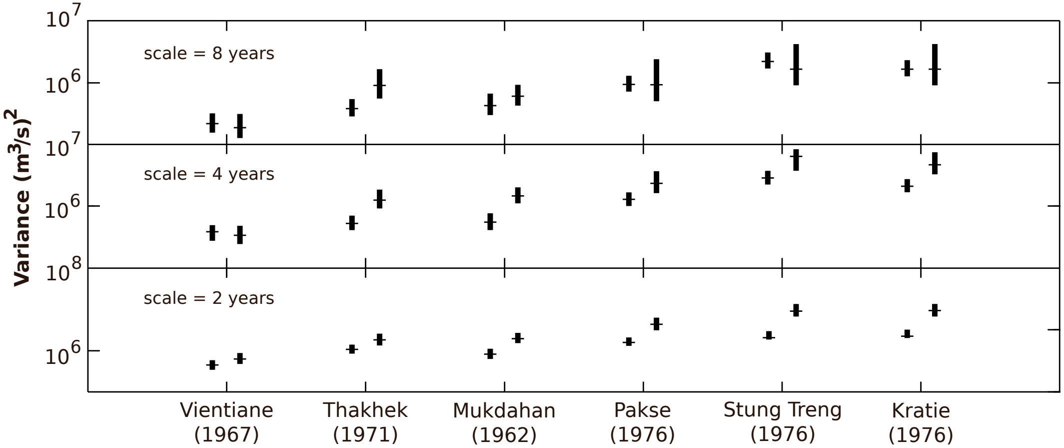

**Fig. 3.** Discrete wavelet variance estimated for the stations depicted in Fig. 1. Step changes in variance were detected and variance before and after the change is shown with confidence intervals. In the southernmost stations, this change occured in 1976. The changes are significant for those changes where the confidence intervals do not intersect.

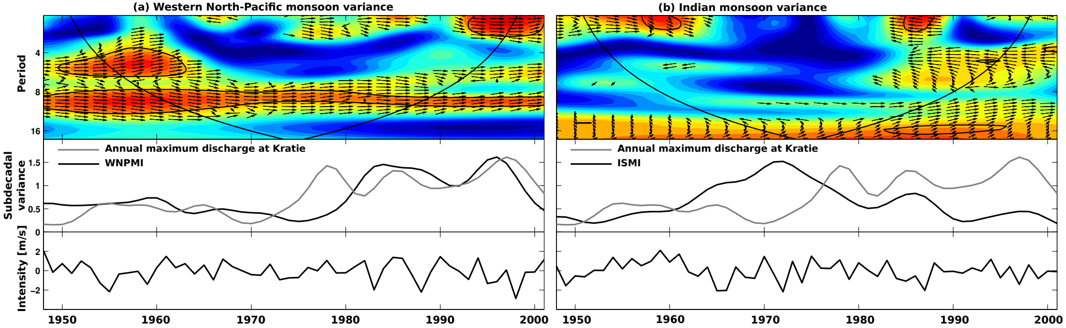

**Fig. 4.** **(a)** Phase coherence between the WNPM index and annual maximum discharge at Kratie (top). The y-axis shows the period of the oscillation and the x-axis the year. Warm colors represent high coherence between the two signals. Significant periods and years are surrounded by a black contour. The arrows show the phase between the two signals: arrow pointing to the right means 0°. The centre panel shows the 1 to 10 yr moving variance as given by the *Morlet* wavelet for the same variables. The lower panel is the monsoon index time series. **(b)** same as in **(a)**, but for the IM index.

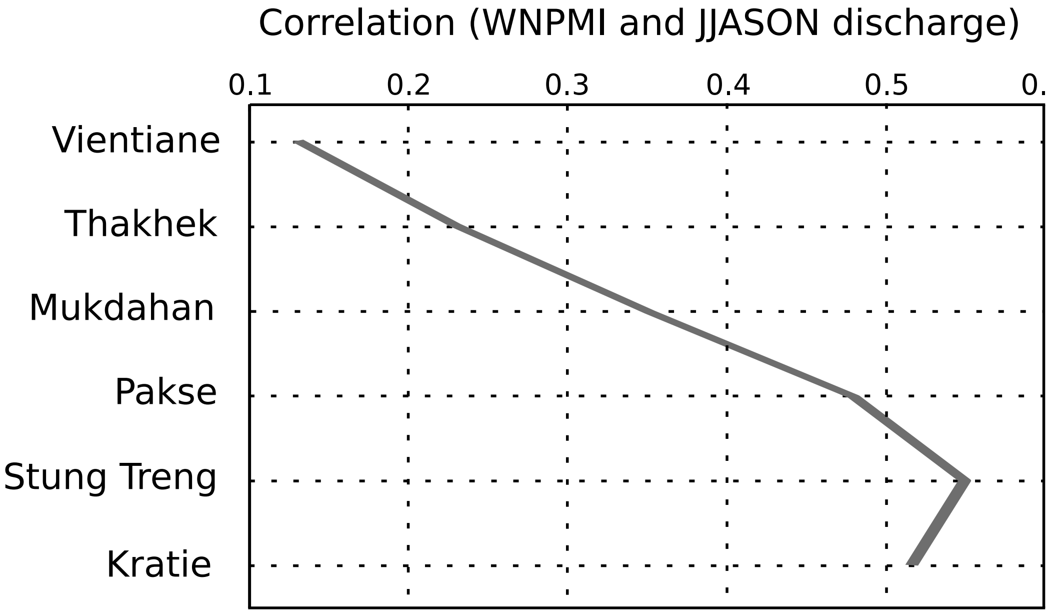

**Fig. 5.** The line shows the north-south evolution of the Pearson correlation between the JJASON average discharge and the WNPM index.

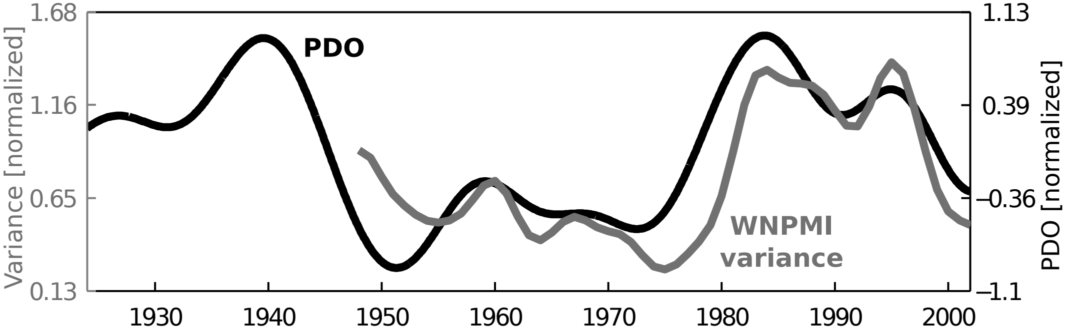

**Fig. 6.** The interdecadal mode of the Pacific Decadal Oscillation resembles the enhancements of the WNPMI subdecadal variance.