Impacts of climate variability on streamflow in the Mekong River: an interesting challenge for hydrological modelling

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Abstract

Historical records indicate that it is often a case of 'all or nothing' in the Mekong River basin, with several years displaying a pattern of abnormally low streamflow persisting for the majority of the year punctuated by short periods of intense rainfall and severe flooding. This study shows that there is a strong relationship between the El Niño/Southern Oscillation (ENSO) and these 'all or nothing' years. 'High' (>30000 m^3/s) streamflow events occur almost every year in the Mekong River. However, the increase in streamflow leading up to peak events during El Niño years is more rapid than La Niña and Neutral years resulting in short periods of 'high' streamflow and 'flash' flooding. The streamflow preceding and following the peak event(s) during El Niño years is therefore very low due to large proportions of the total annual streamflow (which is usually lower than average during El Niño) occurring over very short time periods (i.e. the 'all or nothing' pattern). Current work is focussed on better representation of the physical processes that cause hydro-climatological variability in order to decrease the uncertainty in hydrological predictions, particularly when simulating rapidly developing high flow events and especially for areas where the influence of climate variability is marked. More accurate simulations of hydrological conditions under different future scenarios will then be possible enabling better determination of how we will cope with the changing Mekong River.

Keywords

BTOPMC; climate change; decadal; inter-annual; drought; flood; water resources; University of Yamanashi Hydrological Model (YHyM)

INTRODUCTION

The Mekong River (Figure 1) is the 12th longest river in the world (~ 4,800 kilometres) and the longest and most important in Southeast Asia. Over 60 million people from the developing countries of China, Burma, Thailand, Cambodia, Lao and Vietnam depend on it for food, water, transport and many other aspects of their daily lives. While the Mekong's annual high and low flow cycles are essential for sustainable agriculture and river health, the severe flooding that regularly occurs during the "wet" season (July to November) causes numerous deaths and significant damage. Historical records indicate that it is often a case of 'all or nothing' in the Mekong River basin (MRB), with several years displaying a pattern of abnormally low streamflow persisting for the majority of the year punctuated by short periods of intense rainfall and severe flooding. Similar inter-annual variability in hydro-meteorological variables at many locations around the world has been linked to the global ocean-atmospheric circulation pattern known as the El Niño/Southern Oscillation (ENSO) (e.g. Diaz and Markgraf, 2000; Chiew and McMahon, 2002). In this study the relationship between the ENSO and hydro-meteorological variables in the MRB is investigated. In particular, MRB precipitation and streamflow records are analysed to determine whether there is any association with the ENSO, especially in the 'all or nothing' years. Also discussed is the need for hydrological models to better represent the physical processes that cause hydro-climatological variability in order to decrease the uncertainty in hydrological predictions, particularly when simulating rapidly developing 'peak' flow events (i.e. 'flash' flooding) and especially for areas where the influence of climate variability is marked.

STUDY AREA AND DATA

In order to investigate the relationship between ENSO and hydrological variability in the MRB daily precipitation data (1972-2000) from 64 stations throughout the MRB and daily discharge data (1972-1992) from Pakse is used – this data is provided by the Mekong River Commission. Figure 1 shows the location and digital elevation of the MRB as well as the spatial distribution of the 64 precipitation stations used in this study and the location of the Pakse discharge station. The upstream total drainage area of Pakse is 545000 km^2 and the long-term average annual (January to December) precipitation of the basin is approximately 1570 mm. However, the actual annual precipitation and discharge totals vary significantly in space and time (see Figure 2).

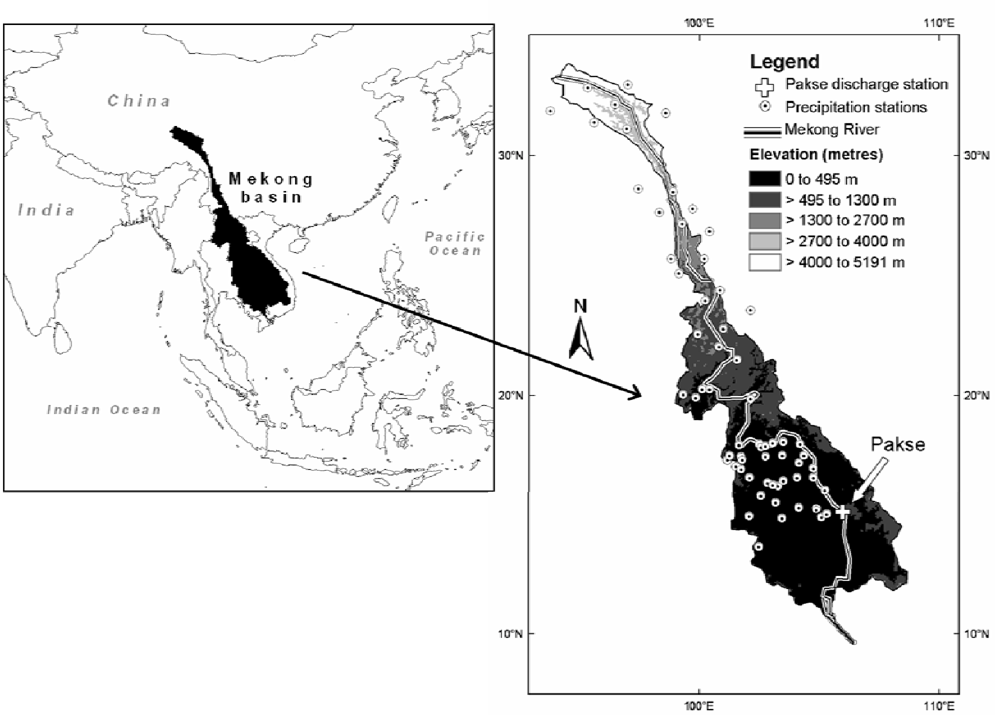

Figure 1. Location and digital elevation of the Mekong River basin. Also shown are the 64 precipitation stations used in this study and the location of the Pakse discharge gauging station.

Precipitation and discharge in the Mekong River basin

Figure 2 shows the average annual precipitation (January 1972 to December 2000) for each of the 64 precipitation stations used in this study. It can be seen that marked deviations from the annual basin average (1570 mm) are apparent. The northern third of the MRB is noticeably 'drier' than the long-term annual basin average and the basin becomes progressively 'wetter' as the latitude approaches the equator, with the majority of the southern third of the MRB wetter than the long-term annual basin average. The 'wettest' area of the basin is the region around station 170406.

To illustrate the temporal variability (and to further demonstrate the spatial variability) of MRB precipitation Figure 2 also displays box plots showing the monthly distributions of precipitation from January 1972 to December 2000 for six 'representative' stations and the monthly discharge distributions at Pakse (January 1972 to December 1992). Although monthly distributions for only six precipitation stations are shown, these 'representative' stations adequately illustrate precipitation patterns of the nearby stations that have similar average annual precipitation. From the box plots in Figure 2 it can be seen that the majority (more than 80% of the annual total) of the MRB's precipitation falls between May and October while most of the discharge at Pakse occurs between June and November. The large 'boxes' (inter-quartile ranges) and substantial differences between minimum and maximum values for the May to October monthly precipitation (and June to November monthly Pakse discharge) distributions indicates that significant year to year variability exists during these months.

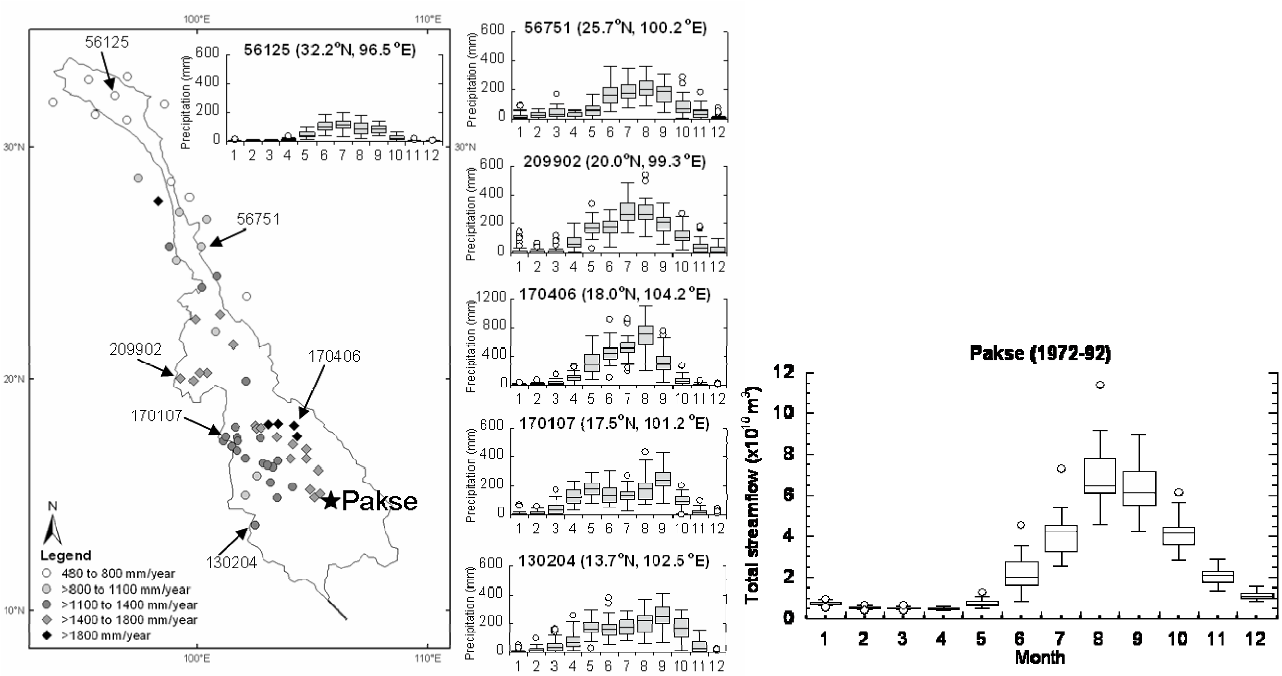

Figure 2. Average annual (1st January 1972 to 31st December 2000) precipitation at the 64 precipitation stations used in this study. Monthly distributions at 6 'representative' precipitation gauges (Note that the y-axis on the box plot for station 170406 has a maximum of 1200mm) and the Pakse (1972-1992) discharge gauging station are also shown.

IDENTIFICATION OF ENSO EVENTS

To determine the impacts of ENSO in the MRB each year is assigned an ENSO classification (either El Niño, La Niña or Neutral) based on the six-month October to March average Multivariate ENSO Index (MEI) value (Wolter and Timlin, 1993; 1998). This method and ENSO index combination has been demonstrated to be the most robust for the time period being investigated (Kiem and Franks, 2001). May to October precipitation totals at each precipitation station (and June to November discharge totals at Pakse) are then stratified into El Niño, La Niña and Neutral phases based on the ENSO classification for the relevant year. Stratified precipitation (and discharge) totals at each precipitation station, and at Pakse, are then compared to determine the relationship between the different ENSO phases and MRB precipitation and discharge. The ENSO analysis is only performed on May to October precipitation totals and June to November discharge totals as Figure 2 shows that minimal inter-annual variation occurs in MRB precipitation and discharge totals outside the periods indicated. Therefore, it is assumed (and has been confirmed by the authors) that the impact of the ENSO on hydro-climatic data in the MRB 'dry' season is also minimal.

RESULTS

ENSO impacts on precipitation and discharge

No significant difference was found between the precipitation (and discharge) in the La Niña and Neutral phases and therefore these two groups were combined to form a 'non-El Niño' group. Figure 3(a) illustrates the impacts that ENSO has on May to October total precipitation averaged over the whole Mekong Basin while Figure 3(b) demonstrates the impact that ENSO has on June to November discharge at Pakse.

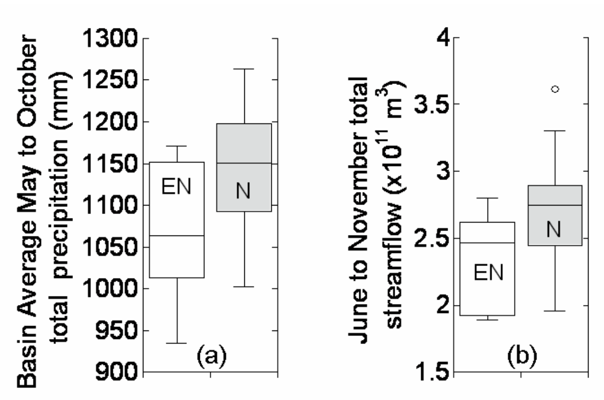

Figure 3. (a) Basin average May to October precipitation totals (1972-2000) and (b) June to November discharge totals (1972-1992) at Pakse during El Niño (EN) and non-El Niño (N) events.

Fifty-seven out of 64 stations displayed markedly higher rainfall during non-El Niño years with the mean basin average May to October total precipitation more than 8% higher in non-El Niño years than it is during El Niño episodes (this difference is significant at the <5% level). In addition, Kiem *et al.* (2004) showed that the impact of ENSO on discharge totals in the Mekong is magnified (when compared with the impact on precipitation) with average non-El Niño May to October discharge at Pakse more than 15% greater than the average during El Niño years. This implies that, in addition to the precipitation in non-El Niño events tending to be higher than El Niño, a given unit of precipitation will result in much more discharge during the non-El Niño phase. This result demonstrates that ENSO influences both precipitation and the physical processes controlling the precipitation-runoff transformation in the MRB. Therefore, the need for hydrological models to satisfactorily reproduce the inherently non-linear and non-stationary precipitation-runoff relationship is also emphasised. In the current study discharge totals from the six months with the highest discharge and largest year-to-year variability (June to November, see Figure 2) were analysed (Figure 3(b)) and it was found that, as with May to October totals, the discharge during non-El Niño events is significantly higher (more than 16% higher) than it is during El Niño events – 75% of the eight El Niño events that occurred during the 1972-1992 study period had June to November streamflow totals that are less than the long-term average (compared with 35% for all other years). However, more important for water resources management and mitigation of extreme events is the way the streamflow totals are achieved.

ENSO impacts on the magnitude and frequency of 'peak' events

The annual maximum daily flow at Pakse for each year between 1972 and 1992 was obtained and the highest, lowest and average annual maximum daily flow during El Niño and non-El Niño events was compared (Table 1). Also investigated was the relationship between ENSO, the number of 'high' flow days and the number of 'peaks'. 'High' flow days were defined as days when the flow was greater than the threshold of $30000 m^3/s$, which was chosen based on the peaks-over-threshold approach to ensure that, on average, there was more than one peak per year. Events where the daily flow went from below to above the 'high' flow threshold were counted as one 'peak' event – note that it is possible to have more than one 'peak' per year.

Table 1 shows that, in addition to influencing seasonal precipitation and discharge totals, the ENSO also impacts the magnitude of peak events, as well as the persistence of 'high' flows (i.e. floods). The average (highest) annual maximum flow is approximately 8% (20%) greater during non-El Niño events than it is during El Niño. In addition, the number of 'high' flow days tends to be lower during the El Niño episodes. These two results, combined with the fact that the number of 'peak' events is similar during all ENSO phases, suggests that even though 'high' flows are possible during El Niño events the magnitude of these floods, and the time they last for, will be lower during El Niño events.

Table 1. Relationship between ENSO and annual maximum flow, number of 'high' flow days and number of 'peak' events as Pakse.

	El Niño	Non-El Niño
Average annual maximum flow (m^3/s)	35875	38600
Highest annual maximum flow (m^3/s)	47600	57800
Lowest annual maximum flow (m^3/s)	24600	28300
Average number of 'high' flow days	11	18
Average number of 'peak' events	1.1	1.5

The implication this has on flood risk in the MRB is demonstrated by subjecting the annual maximum daily flow at Pakse to a Bayesian flood frequency analysis (Kuczera, 1999) first using all years, second using just El Niño years and finally using the remaining non-El Niño years. Figure 4 shows the flood frequency curve (along with the associated 90% confidence limits) obtained when all years were analysed. The width of the 90% confidence interval indicates that significant inter-annual variability exists in the annual maximum flows at Pakse. In fact, Kiem *et al.* (2003) have recently shown that the traditional flood frequency analysis assumption that flood peaks are independent and identically distributed is invalid, particularly for areas where climate variability impacts are marked which, as Table 2 indicates, appears to be the case in the MRB. Table 2 shows that the design floods are much more likely to occur during non-El Niño years and that long-term flood risk, calculated based on the annual maximum flow from all years together (i.e. the traditional flood risk assumption), is consistently under- or over-estimated (depending on the ENSO phase).

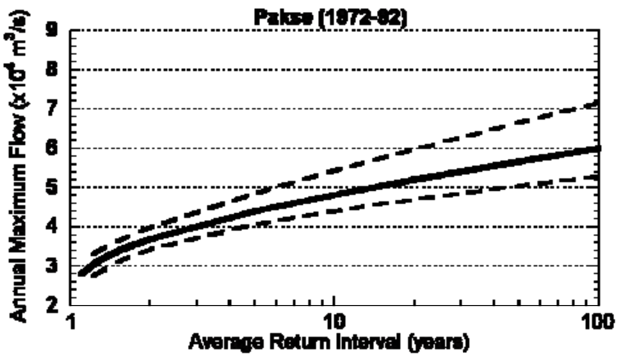

Figure 4. Flood frequency curve (solid line) and the 90% probability limits (dashed lines) at Pakse for the period 1972 to 1992.

Annual Maximum Flow (m^3/s)	Average probability that flow of this magnitude will occur		
	ALL years	El Niño	non-El Niño
27869	90%	83%	100%
36842	50%	33%	57%
43929	20%	10%	25%
48162	10%	5%	14%
51962	5%	2%	9%
59918	1%	0.5%	2.2%

Table 2. Average probability of the design floods (1-in-10 year flood, 1-in-100 year flood etc. calculated based on data from ALL years) occurring in El Niño and non-El Niño years.

ENSO impacts on the daily increase in streamflow prior to 'peak' events

As mentioned in the introduction, 'all or nothing' years, with abnormally low streamflow persisting for the majority of the year punctuated by short periods of intense rainfall and severe flooding, are quite common in the MRB. As shown in the previous sections, the years with abnormally low precipitation and streamflow are closely linked to the El Niño phase of the ENSO. Anecdotal evidence suggests that there is also a relationship between El Niño events and the short, intense rainfall episodes which punctuate the long dry periods, often leading to 'flash' flooding. For example, Oondara (1999) compiled a list of recorded floods and droughts in the MRB between 1965 and 1995 in which the majority of flood events were associated with non-El Niño events, as supported by the results in this paper. However, noticeable from this list was the fact that of the 10 El Niño events that occurred between 1965 and 1995 nine were associated with drought conditions and six of the nine drought-linked El Nino events were also associated with flooding at some stage in the year (note that the converse did not occur, that is no non-El Niño were associated with flooding and drought). To further investigate this relationship the increase in daily Pakse streamflow prior to 'peak' events during El Niño and non-El Niño events was analysed (Figure 5).

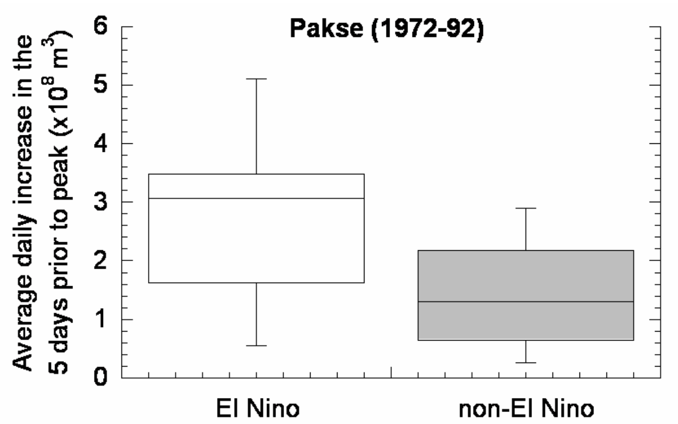

Figure 5. Increase in daily streamflow prior to 'peak' events during El Niño and non-El Niño years.

Figure 5 shows that daily flow prior to a 'peak' event increases at a much faster rate during El Niño years resulting in short (as indicated by Table 1), rapidly developing periods of 'high' streamflow, which explains the 'flash' flooding that commonly occurs during abnormally dry years (i.e. 'all or nothing'). This counter-intuitive result also means that, with respect to water resources and agricultural production, the dry periods generally associated with El Niño events are actually a lot worse than the monthly, seasonal or annual rainfall and discharge totals indicate due to large proportions of the total annual rainfall/streamflow occurring over very short time periods – and disappearing before anyone has time to utilise the extra water as most effort is put into mitigating the negative effects of such a sudden abundance of water.

In summary, El Niño events are typically associated with significantly lower MRB rainfall and streamflow totals than those experienced in non-El Niño years. The magnitude of the annual maximum daily flow, the number of 'high' flow days and the probability of the various design floods occurring also tends to be lower during El Niño episodes. Despite this, when a 'high' flow event does occur during an El Niño event the increase in daily streamflow prior to the peak is much more rapid than that observed in non-El Niño episodes. This more often than not leads to 'flash' flooding, that is difficult to predict and mitigate, preceded and followed by drought conditions (the severity of which is masked in the monthly, seasonal and annual precipitation/discharge totals by the short periods of heavy rainfall. Of course flooding still occurs, in fact is more likely to occur, in non-El Niño years, however these floods tend to be associated with persistent 'high', or gradually increasing, streamflow and are therefore easier to predict and manage so as to minimise negative impacts and maximise utilisation of the extra water.

CONCLUSIONS

This study shows that the ENSO has a significant influence on hydro-meteorological variables in the MRB, however this influence is a lot more complex than revealed by previous studies which have concentrated on the impact of ENSO on monthly, seasonal or annual rainfall and streamflow totals (e.g. Kiem *et al.*, 2004; Xu *et al.*, 2004). The annual and seasonal (May to October precipitation and June to November discharge at Pakse) are significantly lower during El Niño years. More important for water resources management and mitigation of extreme events is the way the streamflow totals are achieved. When El Niño, La Niña and Neutral years are compared it is found that: (1) the magnitude of the annual maximum daily flow is lower during El Niño events; (2) the number of 'high' flow (>30000m^3/s) days during El Niño years is lower than for other years; (3) the probability of the various design floods occurring also tends to be lower during El Niño; and (4) the daily increase in streamflow prior to peak events is markedly higher during El Niño years. Whilst 'high' streamflow events occur almost every year in the Mekong River, the increase in streamflow leading up to peak events during El Niño years is more rapid than La Niña and Neutral years resulting in short periods of 'high' streamflow and 'flash' flooding. The streamflow preceding and following the 'high' flow event(s) during El Niño years is therefore very low due to large proportions of the total annual streamflow occurring over very short time periods (i.e. the 'all or nothing' pattern). Flooding during La Niña and Neutral years is also common, however these floods tend to be associated with persistent 'high', or gradually increasing, streamflow and are therefore easier to predict and manage than the 'flash' flooding common in El Niño years.

Applications of hydrological models to the MRB, and other basins in Monsoon Asia, have encountered difficulties in accurately simulating, and therefore predicting, the 'all or nothing' events whilst also maintaining adequate model performance during other years. Current work, utilising the University of Yamanashi Hydrological Model (YHyM; Takeuchi *et al.*, 2005), which incorporates the physically based distributed hydrological model BTOPMC (Takeuchi *et al.*, 1999; Ao *et al.*, 2003) and a physically based-spatially distributed evapotranspiration model (Zhou *et al.*, 2004), is focussed on better representation of the physical processes that cause hydro-climatological variability in order to decrease the uncertainty in hydrological predictions, particularly when simulating rapidly developing 'high' flow events and especially for areas where the influence of climate variability is marked. More accurate simulations of hydrological conditions under different future scenarios (e.g. land use change, ground water depletion, changes in reservoir operation, climate variability and possible climate change, etc.) will then be possible enabling better determination of how we will cope with the changing Mekong River.

Current consensus is that, due to climate change, flooding in the MRB is becoming worse, with every year from 1997 to 2002 associated with severe Mekong River flooding. Under many projected climate change scenarios this increasing-severity-and-frequency of flooding trend is expected to continue, painting a somewhat negative picture for the MRB. However, recent work focussed on Eastern Australia has shown that decadal to multi-decadal periods of enhanced and more frequent flooding are not unusual and in fact are closely related to naturally varying ocean-atmospheric circulation patterns, namely the Inter-decadal Pacific Oscillation (IPO) and ENSO (Power *et al.*, 1999; Kiem *et al.*, 2003). Abnormally low Pacific Ocean sea-surface temperatures persisting for inter-decadal periods (i.e. negative IPO phase) are associated with a higher frequency of La Niña events and enhanced ENSO impacts in Eastern Australia. While it is difficult to confirm whether similar relationships exist in the MRB, due to the lack of long-term data necessary for multi-decadal analysis, the fact that the 1999/2000 transition from positive to negative IPO phase has corresponded with an upward shift in MRB flood frequency and severity since 1997 is a striking coincidence. Therefore, in order to really determine how we will cope with our changing rivers and to achieve sustainable water resources management and accurate estimates of the risks of extreme climatic events (e.g. floods and droughts) it is necessary to establish and incorporate multi-temporal climate variability insights into prediction, simulation, design and decision making processes. In particular, hydrological models should be tested to ensure that the simulated output reproduces the natural variability evident in the observed record – or in the case of ungauged basins the variability that would be in the observed record if it existed. This is especially important when predicting the hydrological response under future climate scenarios. Any future climate scenarios proposed, and the measures adopted to sustainably manage water resources under these scenarios, should include and account for naturally occurring climate variability impacts, such as those illustrated in this study.

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