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Relationship between ENSO and snow covered area in the Mekong and Yellow river basins

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Abstract Recent applications of the University of Yamanashi Hydrological Model (YHyM) to the Mekong and Yellow river basins reveals significant inter-annual variability in observed discharge during post-winter months (i.e. March to June/July. The impact of the El Niño/Southern Oscillation (ENSO) during these months is minimal and therefore the variation in observed discharge is not explained by variation in post-winter precipitation. This study investigates the relationship between ENSO, winter snow accumulation and post-winter snowmelt as a potential cause of the observed inter-annual variability in post-winter discharge. The results indicate that El Niño (La Niña) years are associated with above (below) average snow covered area (SCA) in both the Mekong and Yellow river basins and therefore the inter-annual variability in observed post-winter discharge is related to ENSO. This study emphasises the need for accurate SCA and snowmelt models in order to reduce uncertainty in hydrological predictions for basins with some percentage of SCA, even if this percentage is not very large. In addition, this study illustrates a significant, and potentially predictable, impact of natural climate variability on a global water resource that will become increasingly important as the demand for water increases in the future, particularly as less developed countries become more developed.

Key words BTOPMC; climate change; climate variability; precipitation; snow; streamflow; University of Yamanashi Hydrological Model (YHyM)

INTRODUCTION

Numerous studies have identified the El Niño/Southern Oscillation (ENSO) as a significant source of inter-annual hydrometeorological variability in many parts of the world (e.g. Diaz & Markgraf, 2000; Chiew & McMahon, 2002), including the large Mekong and Yellow river basins (e.g. Glantz, 2001; Kiem *et al.*, 2004) which are located in southeast Asia and China, respectively (see Fig. 1). Over the majority of the Mekong River basin (MRB) and in north China, where the Yellow River basin (YRB) is primarily located, El Niño events are typically associated with lower than average precipitation and discharge during the Northern Hemisphere summer and autumn (and sometimes winter). ENSO has minimal impact on spring (March–May) precipitation, and discharge that occurs as a result of spring precipitation, because this period usually represents a transitional stage in the ENSO cycle (i.e. the time when new El Niño or La Niña events usually initiate and old ones finish). However, recent applications of the

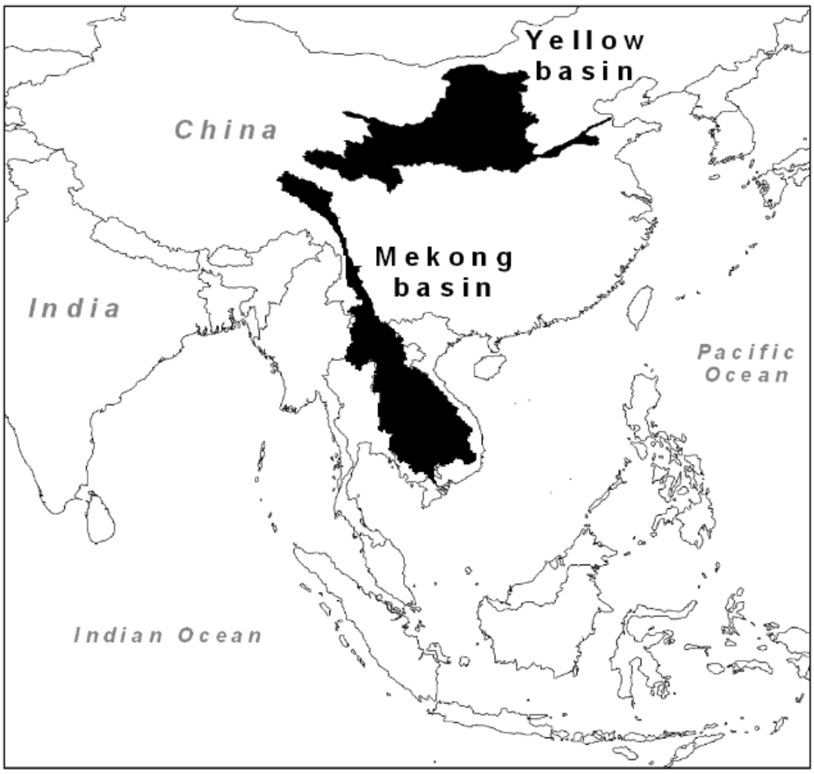

Fig. 1 Location of the Mekong and Yellow river basins.

University of Yamanashi Hydrological Model (YHyM; Takeuchi *et al.*, 2004), which incorporates the physically-based distributed hydrological model BTOPMC (Takeuchi *et al.*, 1999; Ao *et al.*, 2003) and a physically-based spatially-distributed evapotranspiration estimation module (Zhou *et al.*, 2005), to the MRB and YRB reveals that significant inter-annual variability does exist in observed spring discharge that is not related to spring precipitation—in fact spring precipitation in both basins is relatively low and, as mentioned previously, fluctuates little from year to year due to minimal impact of the ENSO from March to May.

In addition to rainfall, another extremely important source of water for many basins, particularly in spring, is the contribution from snow that accumulates during winter and then melts during the post-winter months. In the Northern Hemisphere, the maximum snow covered area (SCA) during winter (December–February) is approx. 46.3 million km^2 (or about 47% of the total Northern Hemisphere land surface), with a volume of approximately 10 000 km^3 (IPPC, 1996). While the majority of the SCA occurs at mid- to high latitudes and in mountainous areas, the contribution of snowmelt to streamflow is still a significant and important source of water at low latitudes and elevations. In this study the SCA in the MRB and YRB is estimated using satellite images and analysed to determine whether there is any relationship with the ENSO. In addition, the winter SCA during the different ENSO phases (i.e. El Niño, La Niña, neutral) is compared with the discharge in the following spring to determine whether, despite not impacting spring precipitation, the ENSO does in fact contribute to inter-annual variability in spring discharge via its impact on snow accumulation during the preceding winter, and the resulting snowmelt in post-winter months.

STUDY REGIONS AND DATA

Mekong River basin (MRB)

The Mekong River is the twelfth longest river in the world (~ 4800 km) and the longest and most important in Southeast Asia. The total area of the MRB is 795 000 km^2 and from Fig. 2 it can be seen that most of this area is located below 2700 m. The long-term average annual (January–December) precipitation in the MRB is approximately 1570 mm with the majority of this occurring from May to October as a result of the southwest monsoon. However, actual annual precipitation totals vary significantly in space and time (see for example Kiem *et al.*, 2004). Observed daily discharge (1972–1992) from the Pakse discharge station (Fig. 2) is used to determine the relationship between winter SCA and streamflow in the following months. This relationship is investigated by comparing the observed daily discharge (which includes melting snow) with the discharge that is due to rainfall alone (i.e. assuming precipitation is rain and not snow and therefore treated as contributing to runoff as soon as it hits the ground). The discharge that is due to rainfall alone is estimated using the evapotranspiration (Zhou *et al.*, 2005) and BTOPMC (Takeuchi *et al.*, 1999; Ao *et al.*, 2003) modules of YHyM to simulate streamflow at Pakse. Daily precipitation

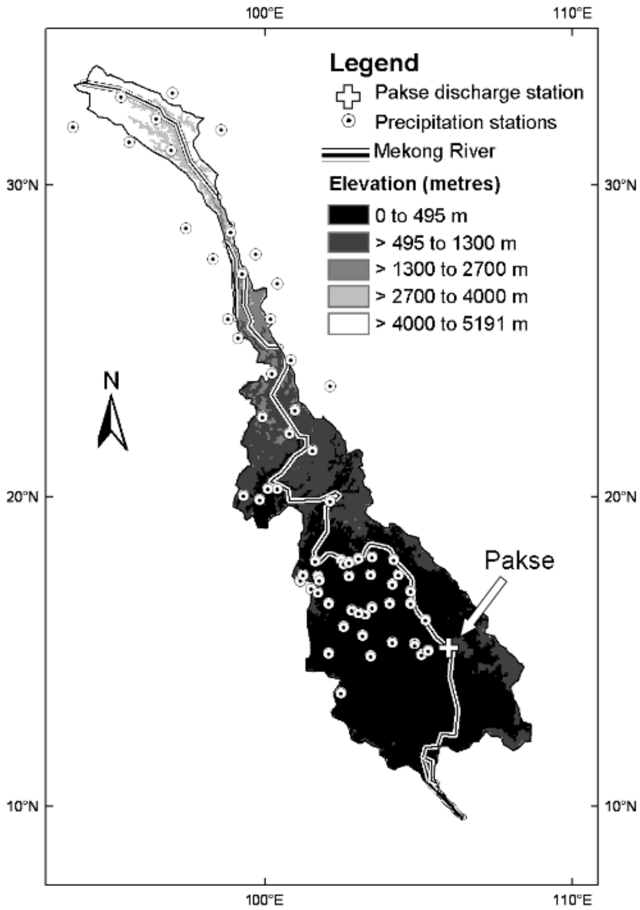

Fig. 2 DEM of the Mekong River basin and the location of the 64 precipitation stations used in this study. Also shown is the location of the Pakse discharge gauging station.

data (1972–1992) from the 64 stations illustrated in Fig. 2 is used as input for BTOPMC. Note that YHyM also includes a module that accounts for snow accumulation and melting, but to simulate discharge due to rainfall alone this module is excluded. The contribution of snowmelt to observed streamflow (and the over estimation of streamflow due to snow being treated as rain) can then be approximated by subtracting the simulated streamflow due to rainfall alone from the observed streamflow (with negative values indicating a period of snow accumulation).

Yellow River basin (YRB)

The Yellow River is the sixth longest river in the world and, after the Yangtze, the second longest river in China (~5464 km). The total area of the YRB is approx. 795 000 km^2 and Fig. 3 shows that, as with the MRB, the majority of this area is also below 2700 m. YRB precipitation is also temporally and spatially variable with El Niño events typically associated with lower than average June to November precipitation (e.g. Glantz, 2001) and average annual precipitation totals decreasing progressively from the southeast (approx. 600 mm) to the northwest (<200 mm). As with the MRB, the majority of the YRB's precipitation also occurs between May and October. Numerous reservoirs have been constructed along the Yellow River which, along with extensive irrigation, significantly alter the natural flow. As a result limited observed discharge data exist which represent the natural state of the Yellow River. Therefore, in order to determine the relationship between SCA and streamflow, the observed discharge from Guide (1972–1985) is used, as the direct impact of human activity (e.g. reservoir operation, irrigation) in the area upstream from Guide (~137 000 km^2) is negligible prior to the construction of Longyangxia Dam in 1986. Figure 3 shows the location of the Guide catchment and the 90 precipitation stations whose data was used as input for BTOPMC in order to simulate the streamflow at Guide due to rainfall alone (note that only nine of these stations have an impact on the discharge at Guide).

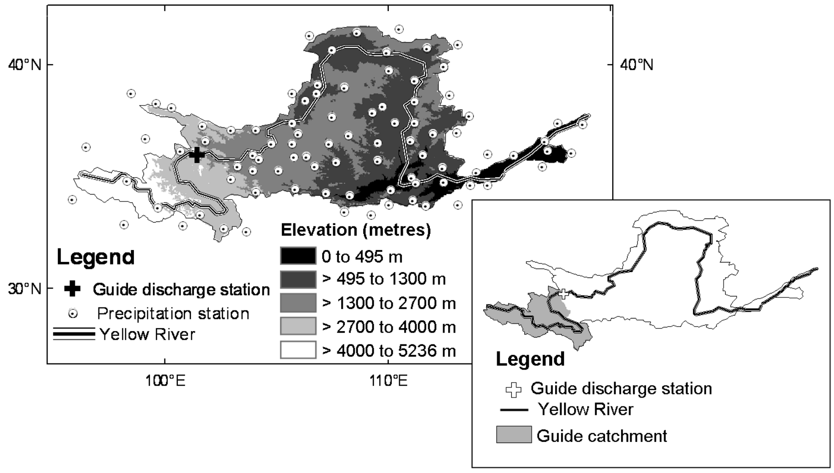

Fig. 3 DEM of the Yellow River basin and the location of the 90 precipitation stations used in this study. Also shown is the location of the Guide discharge gauging station (the Guide catchment is also indicated in the inset).

METHODOLOGY

Estimation of snow covered area (SCA)

NOAA/NASA Pathfinder Advanced Very High Resolution Radiometer (AVHRR) Land data together with the GTOPO30 DEM is used to determine the SCA (%) in the MRB and YRB for each month from July 1981 to September 2001. The Pathfinder AVHRR Land data sets are gridded (0.1 degrees^2 or ~8 km^2) global land surface data derived from AVHRRs on the NOAA/TIROS operational meteorological satellites. The SCA is obtained from visible (Channel 1) and near infrared (Channel 4) images based on the method of Ishidaira *et al.* (2003).

Identification of ENSO events

Each year is assigned an ENSO classification (either El Niño, La Niña or neutral) based on the six-month October–March average Multivariate ENSO Index (MEI) value (Kiem & Franks, 2001). Using this method there are eight El Niño events (1982, 1986, 1987, 1991, 1992, 1993, 1994, 1997) and four La Niña (1988, 1998, 1999, 2000) between 1981 and 2000. Note that an ENSO event begins one year and finishes the next, for example the 1982 El Niño actually spans 1982/83 and is classified based on MEI values from October 1982 to March 1983. Although the timing varies from region to region and from event to event, the impacts associated with ENSO generally begin in the Northern Hemisphere summer, peak during December/January, and fade by February/March in the year after initiation.

RESULTS

SCA in the Mekong and Yellow river basins

Figure 4 displays the distributions of the monthly SCA for the MRB and YRB, as well as the SCA for the Guide catchment. The monthly SCA in the Guide catchment averaged for all months is approximately 30% of the total SCA in the YRB, ranging

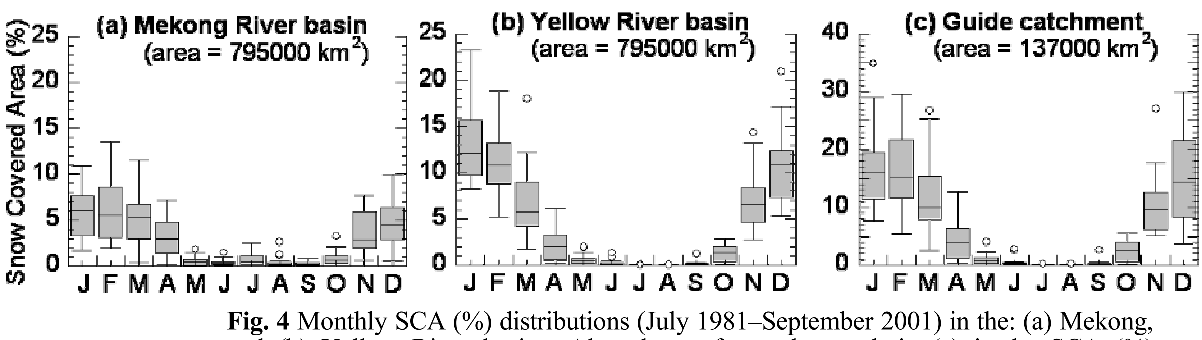

Fig. 4 Monthly SCA (%) distributions (July 1981–September 2001) in the: (a) Mekong, and (b) Yellow River basins. Also shown for each month in (c) is the SCA (%) distributions in the Guide catchment section of the Yellow River basin (see Fig. 3).

from 23% in winter to 34% in summer. Figure 4 shows that the highest SCA occurs from November to March in all three study areas. The large "boxes" (inter-quartile ranges) and substantial differences between minimum and maximum values for the November–March monthly distributions indicate that significant year-to-year variability exists during these months. What is the cause of this inter-annual variability in SCA?

Figures 5 and 6 show, for the MRB and YRB, respectively, the spatial distribution of mean November to March SCA during the year with: (a) minimum and (b) maximum SCA. The mean MRB and YRB November to March SCA averaged over the study

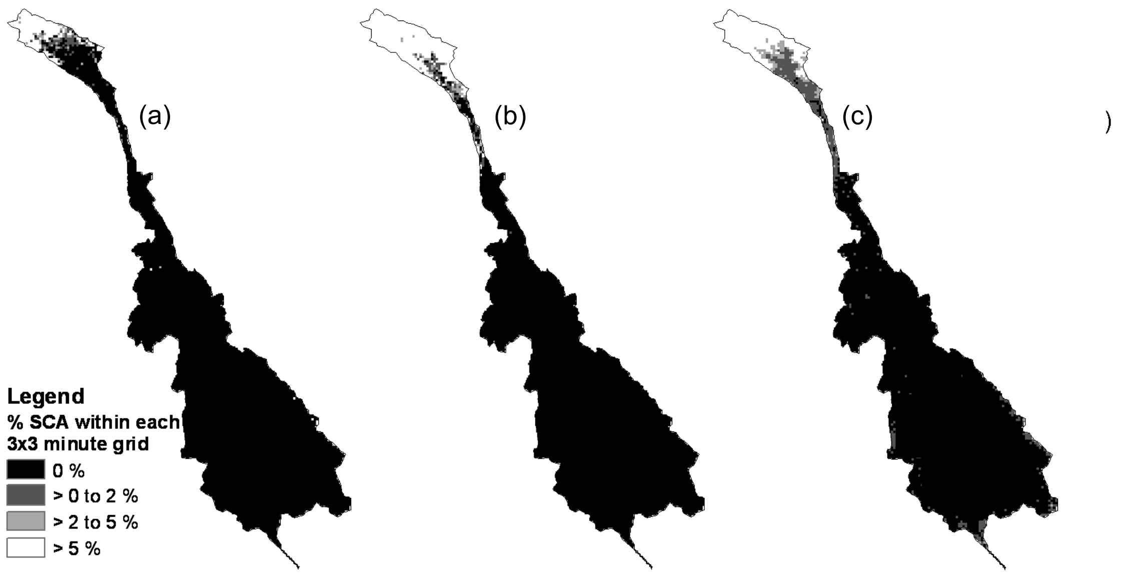

Fig. 5 Spatial distribution of mean November to March SCA in the Mekong River basin: (a) during 1988/89—the year with minimum mean November–March SCA (2.1%); (b) during 1982/83—the year with maximum mean November–March SCA (8.4%); and (c) averaged from 1981 to 2000 (5.1%).

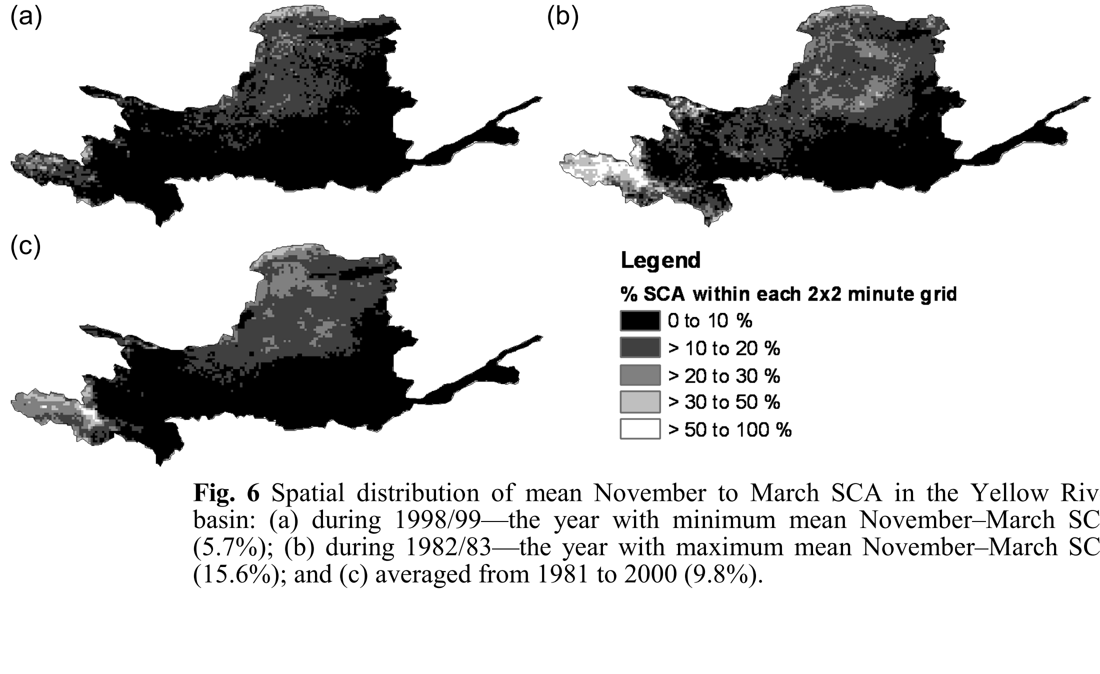

Fig. 6 Spatial distribution of mean November to March SCA in the Yellow River basin: (a) during 1998/99—the year with minimum mean November–March SCA (5.7%); (b) during 1982/83—the year with maximum mean November–March SCA (15.6%); and (c) averaged from 1981 to 2000 (9.8%).

period is shown in Figs 5(c) and 6(c). As expected, the areas with the highest SCA are also the areas with highest elevation (Figs 2 and 3) but more important is the obvious differences between the minimum, maximum and average cases. The mean November–March SCA during the "maximum" year (1982/83 for both the MRB and YRB) is four times greater than it is during the "minimum" year in the MRB (1988/89) and 2.7 times greater than the "minimum" year in the YRB (1998/99). In addition, 1982/83 (high SCA) is an El Niño year and both 1988/89 and 1998/99 (low SCA) are La Niña years which suggest a possible relationship between ENSO and November–March SCA in the MRB and YRB. Is the inter-annual variability in SCA related to ENSO?

Impact of the ENSO on SCA

To investigate this relationship more thoroughly the mean November to March SCA for each year from 1981 to 2000 is stratified into El Niño, La Niña and Neutral phases and the distributions are analysed. While the sample sizes are too small to perform any rigorous statistical tests (i.e. only four La Niña events) there appears to be a reasonable relationship between ENSO and November to March SCA in the MRB and YRB (including the Guide catchment), with El Niño events associated with markedly higher SCA in all study areas (see Fig. 7). On average, November–March SCA in the MRB during El Niño is 12% higher than the 1981–2000 mean (21% lower during La Niña), for the YRB the November–March SCA is 8% higher than average during El Niño (15% lower during La Niña) and for the Guide catchment El Niño events are associated with SCA that is 10% above average (25% below average during La Niña). Does this impact of ENSO on November–March SCA contribute to the inter-annual variability in observed "spring" discharge at Pakse and Guide that is not explained by variability in "spring" precipitation?

Impact of snow accumulation and melting on streamflow at Pakse and Guide

In order to determine the impact of snow accumulation and melting on observed streamflow it is first necessary to determine what the streamflow would be if there was

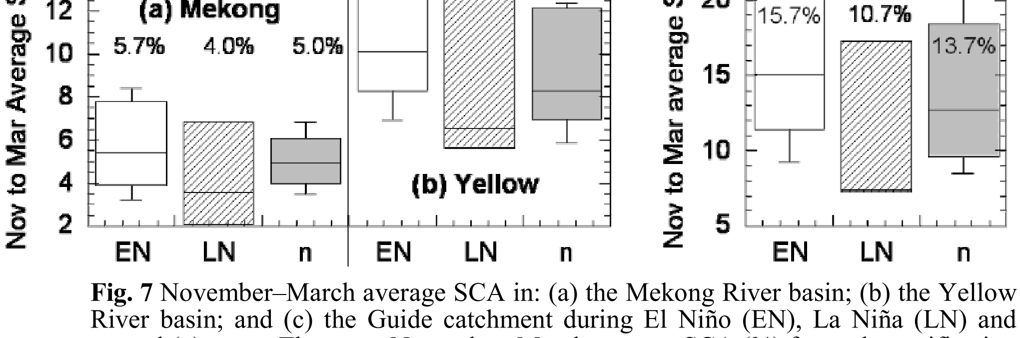

Fig. 7 November–March average SCA in: (a) the Mekong River basin; (b) the Yellow River basin; and (c) the Guide catchment during El Niño (EN), La Niña (LN) and neutral (n) years. The mean November–March average SCA (%) for each stratification is also indicated.

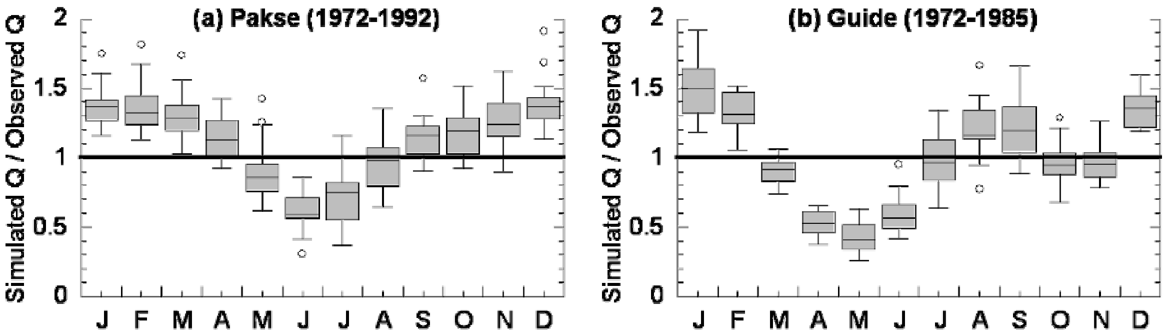

Fig. 8 Monthly distributions of simulated over observed discharge at: (a) Pakse and (b) Guide.

no influence from snow. To do this YHyM is used, without the snow accumulation and melting module, to simulate streamflow due to rainfall alone (i.e. precipitation is always treated as rainfall) at Pakse and Guide. The simulated streamflow is then compared with the observed discharge at Pakse and Guide from 1972 to 1992 and 1972 to 1985, respectively, with the difference between simulated and observed assumed to approximate the influence of snow accumulation and melting. shows, for each month, the distributions of the ratio of simulated to observed discharge. A ratio greater than one indicates an overestimation that is due to precipitation that is snow being treated as rain and therefore converted to runoff as soon as it hits the ground, when in reality the snow accumulates and is converted to runoff at a much slower rate. A ratio less than one indicates an underestimation that is due to the contribution of melting snow not being included in the hydrological simulation. Therefore, when the ratio is less than one the difference between observed and simulated discharge is an indication of the contribution of snowmelt to discharge.

From Fig. 8 it can clearly be seen that for both the MRB and Guide catchment the accumulation of snow from November to March and the melting of snow from May to July (Pakse) and March to June (Guide) has a significant impact on observed discharge—the average contribution from snowmelt at Pakse (May–July) is almost 30% ($\sim 1.9 \times 10^{10}$ m^3) of the total observed discharge while for Guide (March–June) the average contribution from snowmelt is nearly 40% ($\sim 2.7 \times 10^9$ m^3). Therefore, despite the percentage of SCA in both the MRB and Guide catchment being relatively small, the impact of snow accumulated during winter on post-winter discharge is quite significant. Since November–March SCA displays significant ENSO related inter-annual variability, it follows that post-winter streamflow will also vary from year to year due not to ENSO impacts on "spring" precipitation but, instead, to the impact of ENSO on "winter" SCA which in turn affects the amount of water that is contributed, via snowmelt, to streamflow the following March to June/July.

Figure 9 illustrates the relationship between ENSO, November–March SCA in the MRB and discharge at Pakse during the following May–July period. Note that the analysis period was limited by the availability of SCA and observed discharge data. This is why Guide is not shown as the available data only allow analysis of four years (November–March SCA from 1981 to 1984 against March–June streamflow from 1982 to 1985). While the results are inconclusive due to the small amount of data (i.e. only four El Niño and one La Niña), Fig. 9 shows that high (low) November–March

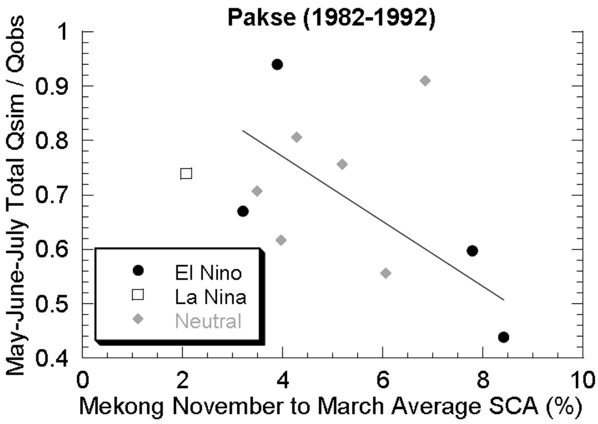

Fig. 9 Relationship between the ENSO, November–March average SCA in the Mekong and the ratio of the simulated to observed discharge at Pakse (May–July total).

SCA, which is more likely to occur during El Niño (La Niña) events, is associated with larger (smaller) snowmelt contributions and therefore higher (lower) than average streamflow at Pakse during May, June and July. Anecdotal evidence suggests that a similar pattern applies in the YRB with the 1982/83 and 1997/98 El Niño events associated with heavy snowstorms on the Tibetan Plateau during winter followed by severe flooding in the Yellow and Yangtze rivers the following spring/summer, while the 1998/99 La Niña was associated with low "winter" SCA (Fig. 6) and lower than average Yellow River streamflow during spring/summer 1999—the Yellow River actually dried up for 42 days in 1999. Therefore, despite the impact of ENSO on precipitation being minimal during the usual ENSO transition period (March–May), it appears that the inter-annual variability in observed post-winter (March–June/July) discharge in the MRB and YRB is still related to ENSO. However, this relationship is with the ENSO event that occurred the previous year and its impact on winter SCA (and the resulting snowmelt in the post-winter months). The fact that ENSO conditions for the upcoming year can usually be identified by at least June/July means that the relationship between ENSO, winter SCA and runoff due to snowmelt in the post-winter months can be utilized to provide important information about streamflow from May to July in the MRB and from March to June in Guide catchment (and probably the remainder of the YRB also) at least eight months in advance. This is extremely useful information for the sustainable management of water resources, agricultural production, and the mitigation of extreme events such as floods and droughts.

CONCLUSIONS

November–March SCA, and the resulting post-winter streamflow due to snowmelt, in the MRB and YRB is influenced by the ENSO, with El Niño years tending to be associated with increased SCA in both study basins. This appears to be the major cause of the observed inter-annual variability in observed post-winter streamflow in the MRB and YRB. Therefore, in addition to significantly impacting precipitation and the associated streamflow during summer, autumn (and sometimes winter) (e.g. Glantz, 2001; Kiem *et al.*, 2004), when the anomalous ocean–atmospheric conditions associated with El Niño and La Niña are at their peak, the impacts of ENSO continue to influence hydrological processes months after the ocean–atmospheric conditions have returned to normal (or even reversed to the opposite phase). Importantly, these insights, along with state-of-the-art ENSO predictions, which identify most El Niño and La Niña events by at least June/July, can be used to obtain information about post-winter streamflow up to eight months in advance.

From this study it is clear that despite only small percentages of the MRB and YRB being classed as alpine or mountainous regions, and the SCA in these basins forming only a small proportion of the SCA for the entire Northern Hemisphere, the impact of snow accumulation and melting on runoff totals is still significant. This emphasizes the need for accurate SCA and snowmelt models in order to reduce uncertainty in hydrological predictions for basins with some percentage of SCA, even if this percentage is not very large. In addition, this study illustrates a significant, and potentially predictable, impact of natural climate variability on a global water resource that will become increasingly important as the demand for water increases in the future, particularly as less developed countries become more developed.

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