Hydrol. Earth Syst. Sci. Discuss., 7, 5991–6024, 2010
www.hydrol-earth-syst-sci-discuss.net/7/5991/2010/
doi:10.5194/hessd-7-5991-2010
© Author(s) 2010. CC Attribution 3.0 License.

Hydrology and Earth System Sciences Discussions

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Uncertainty in climate change projections of discharge for the Mekong River Basin

D. G. Kingston[1,2], J. R. Thompson[1], and G. Kite[3]

[1]UCL Department of Geography, University College London, Gower Street, London, WC1E 6BT, UK
[2]Department of Geography, University of Otago, P.O. Box 56, Dunedin, New Zealand
[3]Bryn Eithin, Cefn Bychan Road, Pantymwyn, Flintshire, CH7 5EN, UK

Received: 6 August 2010 – Accepted: 6 August 2010 – Published: 23 August 2010

Correspondence to: D. G. Kingston (daniel.kingston@geography.otago.ac.nz)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Mekong River Basin comprises a key regional resource in Southeast Asia for sectors that include agriculture, fisheries and electricity production. Here we explore the potential impacts of climate change on freshwater resources within the river basin. We quantify uncertainty in these projections associated with GCM structure and climate sensitivity, as well as from hydrological model parameter specification. This is achieved by running pattern-scaled GCM output through a semi-distributed hydrological model (SLURP) of the basin. These pattern-scaled GCM outputs allow investigation of specific thresholds of global climate change including the postulated 2 °C threshold of "dangerous" climate change as simulated using outputs from seven different GCMs. Detailed analysis of results based on HadCM3 climate scenarios reveals a relatively small but non-linear response of annual river discharge to increasing global mean temperature, ranging from a 5.4% decrease to 4.5% increase. Intra-annual (monthly) changes in river discharge are greater (from −16% to +55%, with greatest decreases in July and August, greatest increases in May and June) and result from complex and contrasting intra-basin changes in precipitation, evaporation and snow storage/melt. Whilst overall results are highly GCM dependent (in both direction and magnitude), this uncertainty is primarily driven by differences in GCM projections of future precipitation. In contrast, there is strong consistency between GCMs in terms of both increased potential evapotranspiration and a shift to an earlier and less substantial snowmelt season. Indeed, in the upper Mekong (Lancang sub-basin), the temperature-related signal in discharge is strong enough to overwhelm the precipitation-related uncertainty in the direction of change in discharge, with scenarios from all GCMs leading to increased river flow from April–June, and decreased flow from July–August.

HESSD

7, 5991–6024, 2010

CC BY

1 Introduction

Changing availability of freshwater resources is likely to be one of the most important consequences of projected 21st Century climate change, critically affecting the potential for sustainable development of life and livelihoods (Bates et al., 2008; Todd et al., 2010). Over Southeast Asia, the most recent projections from the Intergovernmental Panel on Climate Change (IPCC) suggest future increases in precipitation (Bates et al., 2008). At least 80% of the GCMs used in this IPCC assessment show increased annual precipitation across Southeast Asia, together with increases in the intensity of precipitation events and the magnitude and frequency of both extreme wet and dry events (Christensen et al., 2007).

The impacts of hydrological changes resulting from projected changes in climate may be particularly severe for the Mekong River system, given its role as a vital regional resource, providing food, water, transport and livelihoods (Kite, 2001). The Mekong also supports unique and varied ecosystems, with a number of endemic species and large and diverse fisheries. This is important because the Mekong (in part, through its fisheries) provides the staple diet for approximately 300 million people (Hapuarachchi et al., 2008). Particularly productive areas include the Mekong Delta and its associated wetlands, as well as the Tonle Sap lake in Cambodia. However, fisheries and other resources provided by the river are vulnerable to changes in the seasonality of river flow, sediment load and water quality (Costa-Cabral et al., 2008). Indeed, fish catches per fisher have been declining over time (MRC, 2003), although there is some uncertainty as to whether this is, at least in part, due to increasing numbers of fishers (Hapuarachchi et al., 2008). The Mekong is also being impacted by large-scale hydraulic interventions with a focus on hydropower. Two large dams have already been constructed on the Chinese section of the river (at Manwan and Dachaoschan) and further dams are either under construction or planned throughout the river basin (Kite, 2001; Li and He, 2008; Stone, 2010). The two aforementioned Chinese dams have already been controversial in terms of their downstream impacts with uncertainty over

HESSD
7, 5991–6024, 2010

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

their influence on recent variations in flow volumes, sediment loadings and fisheries (Li and He, 2008).

Given the magnitude of projected climatic changes, the importance of water for socio-economic development throughout the region (including the growing influence of hydropower), and the increasing (often trans-boundary) competition for water use in the Mekong, there is a clear need for improved understanding of the potential impacts of climate change on future availability of freshwater resources. Only through such understanding can water resource managers (particularly the basin authority, the Mekong River Commission, MRC) fully evaluate proposed developments and implement appropriate transboundary management strategies. The need for climate change adaptation strategies is particularly prescient for the Mekong given the reliance on the river for agriculture and fish, the vulnerability of the low-lying delta region including large flood-prone areas, and the relative absence of river management infrastructure. This situation is likely to be exacerbated by the projected substantial increases in population, in particular in the lower Mekong Basin (from 55 to 90 million by 2025, MRC 2003). Furthermore, the precipitation elasticity of Mekong river flow has been estimated as generally greater than zero, meaning that changes in precipitation result in proportionately greater changes in river flow (Hapuarachchi et al., 2008).

Previous studies of the hydrological impacts of potential climate change on the Mekong have generally focussed on climate forcings from individual GCMs or the mean climate change from an ensemble of GCMs. For example, Kiem et al. (2008) used output from the Japanese Meteorological Agency GCM for the IPCC SRES A1b scenario and a gridded hydrological model to show that the mean annual number of wet days, precipitation and discharge would increase by 5.2, 6.3 and 11.7%, respectively between 1979–1998 and 2080–2099. Ishidaira et al. (2008) employed a distributed hydrological model and the mean of the Tyndall Centre v2.03 scenario set. Their results suggested increases in future Mekong discharges up to 2080 with the maximum increases occurring in the middle of the 21st Century.

Whilst useful and informative, these previous studies of climate change impacts on Mekong river flow have generally been limited by their adoption of future climate projections from a single GCM or by masking the variation between GCMs through the use of ensemble means. Although GCM simulated temperature can be relatively consistent between GCMs, the same is not true for precipitation. Indeed, projections of future precipitation from different GCMs often disagree even in the direction of change (Randall et al., 2007). For this reason, it is essential that climate change impact studies consider an ensemble of GCMs without resorting to ensemble mean climate change. As part of the wider QUEST-GSI project (Todd et al., 2010; http://www.met.reading.ac.uk/research/quest-gsi/, accessed June 2010), this study addresses the important issue of GCM uncertainty by driving a hydrological model of the Mekong River Basin with outputs from seven different CMIP-3 GCMs (CCCMA CGCM31, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM30, UKMO HadCM3, UKMO HadGEM1). These GCMs are driven by the policy relevant scenario of a 2 °C rise in global mean temperature, a presumed threshold of "dangerous" climate change (Todd et al., 2010). In addition, the hydrological impacts of a progressive change in global mean temperature (from 0.5 to 6 °C) using one GCM, UKMO HadCM3, are also investigated.

2 The Mekong River Basin

The Mekong River is the world's eighth largest in discharge (annual discharge: 475 km^3), 12th largest in length (4350 km), and 21st largest in drainage area (795 000 km^2). It is a major trans-boundary river, originating at over 5100 m a.s.l. in the Tibetan Highlands. The Mekong subsequently flows through the narrow, steep, and in places virtually unexplored Lancang Gorge in China's Yunnan Province before passing through Burma, Laos, Thailand and Cambodia and discharging into the South China Sea from the many distributaries within its delta which lies predominantly within Vietnam (Fig. 1).

HESSD
7, 5991–6024, 2010

The Mekong is initially fed by melting snow in the Tibetan Highlands, with the predominant land cover in the upper half of the Lancang sub-basin consisting of tundra and montane semi-desert. Although snow covers only approximately 5% of the Mekong Basin during November–March (and is negligible at other times), snow storage and subsequent melt has a substantial impact on Mekong runoff (Kiem et al., 2008). Indeed, 34% of mean annual discharge at Pakse (the terminus of the Mekong 2 basin) originates from the Lancang sub-basin. The lower Lancang, Nam Ou, Nam Ngum and upper Mekong 1 sub-basins are dominated by forest (both deciduous and evergreen). The Mekong 1 sub-basin is the largest contributor to annual Pakse discharge (39%). Agriculture forms the greatest land-use type in the lower basin, particularly in the Chi and Mun sub-basins (which together contribute approximately 10% of Pakse mean annual discharge) and within the delta.

The vast majority of the basin experiences a monsoonal climate, with seasonal precipitation the primary source of river runoff. The wet season lasts from mid-May to October, and accounts for over 90% of annual precipitation in many areas. Overall, total annual precipitation ranges from highs of 3200 mm in parts of Laos, to under 1000 mm on the relatively arid Korat plateau in Eastern Thailand (i.e. the Chi and Mun sub-basins). Peak river flow at the head of the delta (Phnom Penh) usually occurs in September or October, with the high flow season extending from June–November. Annual minimum flows occur in March or April.

3 Data and methods

3.1 Data

Baseline climate data for the hydrological model of the Mekong River Basin comprising monthly minimum and maximum temperature, precipitation totals and number of wet days were initially obtained from the $0.5^{\circ} \times 0.5^{\circ}$ gridded CRU TS 3.0 dataset (Mitchell and Jones, 2005), as described in Todd et al. (2010). Monthly data for the 268 grid

HESSD
7, 5991–6024, 2010

cells which cover the river basin were stochastically disaggregated to daily resolution following the procedures developed by Arnell (2003) and further described by Todd et al. (2010). Station-based daily precipitation and temperature data (the basis for local calibration of the daily disaggregation procedure) were obtained from the US National Climate Data Centre (NCDC) global surface summary of the day (GSOD) meteorological stations used by Kite (2001).

Future (monthly resolution) climate scenarios for temperature and precipitation were generated using the ClimGen pattern-scaling technique developed by Arnell and Osborn (2006) and Todd et al. (2010), and later downscaled to daily resolution following the procedure outlined above. ClimGen is a spatial scenario generator (e.g., Hulme et al., 2000), based on the assumption that the spatial pattern of climate change, expressed as change per unit of global mean temperature change, is relatively constant for a given GCM (Arnell and Osborn, 2006). This allows the pattern of climate change from an individual GCM to be scaled up- and downwards in magnitude, enabling specific thresholds of global climate change to be explored (Todd et al., 2010). Scenarios were generated here for a prescribed warming of global mean temperature of 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, and 6 °C using the UKMO HadCM3 GCM, and for a 2 °C warming using six additional GCMs: CCCMA CGCM31, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM30 and UKMO HadGEM1. This subset of CMIP-3 GCMs was derived following the analyses described by Todd et al. (2010) to span a range of "plausible" different modelled global climate futures (e.g. Indian monsoon weakening/strengthening, magnitude of Amazon dieback).

3.2 The SLURP hydrological model

The hydrological model used to investigate climate change impacts on the Mekong River Basin was developed using the Semi-distributed Land Use-based Runoff Processes (SLURP, v.12.7) model (Kite, 1995). This is a physically based semi-distributed hydrological model that operates on a daily time step. The SLURP model has been successfully employed in a range of different environments across the globe. These

HESSD
7, 5991–6024, 2010

cc BY

range from small Canadian wetland basins of less than 1 km^2 (Su, 2000), through catchments of hundreds of square kilometres with very different climatologies including studies in Canada (Armstrong and Martz, 2008), Germany (Viney et al., 2009), Turkey (Apaydin et al., 2006) and South Korea (Kim et al., 2007; Park et al., 2009), to major river basins including upper tributaries of the Indus and Yangtze (Jain et al., 1998; Woo et al., 2009).

The Mekong River Basin has previously been modelled using SLURP, for the period 1994–1998 (Kite, 2001). In this previous study, the basin was divided into 13 sub-basins (Fig. 1) based on the United States Geological Survey (USGS) GTOPO-30 digital elevation model. Land cover types within each sub-basin were derived from the USGS 1 km digital land cover map of the world, with soil parameters generated using data from the FAO World Soil Map (FAO, 1990). The climate data used to drive the original Mekong SLURP model consisted of station-based daily meteorological data from the NCDC GSOD dataset. The whole 1994–1998 period was employed as the simulation period without calibration and daily river flow was shown to be simulated "reasonably well" at a number of gauging stations (Kite, 2001).

The present study started with the same SLURP model, topographic, land cover and soil data, sub-basins and model parameters used by Kite (2001), but with the model run for the much longer 1961–1998 period. In common with other modelling studies undertaken within the QUEST-GSI project (e.g. Hughes et al., 2010; Kingston and Taylor, 2010), a baseline period of 1961–1990 was used for calibration, with the remaining 1991–1998 data used for validation. The input climate data were derived (initially) from the monthly CRU TS 3.0 dataset disaggregated to daily resolution (as described in Todd et al., 2010), rather than the relatively sparse GSOD daily station based dataset. The SLURP model creates spatial averages of each climate variable for each sub-basin, which are then used to drive the model. Although SLURP operates on a daily time-step, results are only considered at a monthly resolution due to the use of a stochastic weather generator to generate daily climate data. As with the Kite (2001) study, the Mekong Basin was only modelled as far as the Pakse gauging

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

HESSD

7, 5991–6024, 2010

Uncertainty in projections for the Mekong

D. G. Kingston et al.

station in Laos (i.e. the terminus of the "Mekong 2" sub-basin) which is upstream of the many distributaries of the river's extensive delta. The modelled area was therefore 550 000 km^2 rather than the total 795 000 km^2 of the whole Mekong Basin.

3.3 Calibration and validation of the SLURP hydrological model

Data from three gauging stations were available for calibration of the SLURP hydrological model: Chiang-Saen (the terminus of the Lancang sub-basin, with an upstream area of 228 000 km^2), Ubon (the Chi, Mun and Chi-Mun sub-basins, 122 390 km^2), and Pakse (the entire modelled area, i.e. the terminus of the Mekong 2 sub-basin). Model calibration was undertaken sequentially from upstream to downstream (i.e. Chiang-Saen and Ubon before Pakse), and was particularly focussed on the Chiang-Saen and Pakse stations as the combined Chi, Mun and Chi-mun sub-basins (i.e. Ubon gauging station) contribute only 10% of the mean annual flow at Pakse (in comparison to 34% from Lancang).

Initial runs of the SLURP model for the 1961–1990 calibration period indicated that it would be necessary to modify existing values of model parameters in order to gain a satisfactory fit between modelled and observed discharge. Modelled discharge using the original (Kite, 2001) parameter values was too high in all months whilst the transition to and from the high flow season was too gradual. The need for re-calibration was expected given the different time period for which the model was being run and the different climate data being used. This is in common with previous research that has shown that hydrological models may require recalibration when meteorological inputs are changed from station-based records to gridded datasets (Mileham et al., 2008; Xu et al., 2010).

The calibration of the Mekong model was determined by the SLURP model structure and was based on modifications to parameters describing (i) water transport through the soil profile which vary between different land covers (the retention constants and capacities of the fast and slow soil stores) and (ii) those which vary between sub-basins (evaporation, Manning's roughness and field capacity coefficients). Initial minor manual adjustment of SLURP parameters proved ineffective, with the model continuing to simulate monthly discharges which were substantially higher than those of the observed records at the three gauging stations, particularly during the rising and descending limbs of the annual flood peak. The Shuffled Complex Evolution method of model autocalibration developed at the University of Arizona (SCE-UA) is embedded within SLURP, but application of this method failed to improve the model calibration. This is thought to be because autocalibration within SLURP can only be performed at a daily time-step, and the disconnect between daily temperature, precipitation and discharge introduced by artificially generating daily weather data prevents the autocalibration routine from working effectively at this temporal resolution.

Following these initial calibration attempts, more substantial changes were made to the model. The potential evapotranspiration (PET) routine was changed from the original Penman-Monteith method to the less data-intensive and more empirical temperature-based Linacre method. Although this resulted in substantial improvements, including lower modelled discharge and a better match to the shape of the observed annual hydrograph, results were still considered to be beyond the bounds of acceptability.

Improvement in model performance following the adoption of a less data-intensive PET method suggests that data quality may be an issue. There are two principal reasons why this may be the case. Firstly, Penman-Monteith PET requires humidity, wind speed and net radiation data in addition to temperature. The former variables are typically less reliable in gridded datasets, due in part to measurement difficulties and a relatively limited number of data points, particularly for the latter two variables (e.g., New et al., 1999). The second factor is more specific to the upper section of the Mekong River Basin (i.e. the Lancang sub-catchment), where the river passes through a series of very narrow gorges. In places, these gorges are substantially narrower than the 0.5° resolution of the input climate data. Coupled with the likely high spatial variability of local climate over this complex terrain and the relatively poor coverage of station data used to construct the gridded CRU data, the representivity of gridded datasets

HESSD
7, 5991–6024, 2010
Uncertainty in projections for the Mekong
D. G. Kingston et al.

is liable to be poor in such areas. This is likely to be particularly prescient for precipitation, which can exhibit high spatial variability even over relatively homogeneous terrain. In light of the potential poor representivity of the CRU precipitation data, an alternative precipitation dataset, the University of Delaware global precipitation dataset (UDel) based on Legates and Wilmott (1990), was used to investigate whether poor model performance was due, in part, to the precipitation data used to drive the model.

Initial results using the UDel precipitation dataset produced a marked improvement in model performance compared to those based on the original CRU TS 3.0 data. Although this is initially surprising (the CRU database contains more station data points than UDel), these results follow previous findings (Hughes et al., 2010). One possible reason for this apparent contradiction is that the CRU dataset intermittently captures more detail in regional precipitation than UDel, but that not all of this regional detail is relevant for the Mekong River Basin (i.e. occurs beyond the basin boundary). Furthermore, as a result of aggregating and smoothing these data to create a gridded product, some rainfall events may be erroneously introduced to or omitted from the Mekong Basin, especially in the narrow and topographically complex Lancang section.

Further manual adjustment of model parameters was undertaken following the guidelines provided by Kite (2008). UDel-driven simulation of Pakse mean monthly discharge was bought substantially closer to the observed values (Figs. 2a and 3a). However, discharge was still slightly underestimated during the peak and low flow seasons, and slightly overestimated during the transition months. It was not possible from reasonable parameter adjustment to further increase modelled river flow during the high and low flow seasons without also increasing the overestimation of flow during the transition seasons. A good fit was also obtained for Chiang-Saen (Figs. 2b and 3b). Although peak and low season discharges were successfully captured for Ubon, as at Pakse rising and descending limb discharges were generally too high (Figs. 2c and 3c). The Nash-Sutcliffe coefficients (R2) for monthly discharge for the 1961–1990 calibration period are 0.89 (Pakse), 0.78 (Chiang-Saen) and 0.44 (Ubon). According to the classification scheme of Henriksen et al. (2008) the R2 value for Pakse is “excellent” and that

HESSD
7, 5991–6024, 2010

for Chiang-Saen "very good". The relatively low value for Ubon (classified as "poor") is likely to reflect the aforementioned discrepancies in the simulation of the rising and descending limbs of the annual hydrograph. The simulated Pakse discharge compares favourably with previously published models of the Mekong (e.g., Kite, 2001; Jayawardene and Mahanama, 2002; Hapuarachchi et al., 2008; Ishidaira et al., 2008; Västilä et al., 2010).

The performance of the model varies little between the calibration and validation periods at Pakse (Fig. 2a). Similarly, little change in the correspondence between the model and observations occurs for Chiang-Saen and Ubon (Fig. 2b and c, respectively) with the caveat that observed data is only available up to 1997 for the former, and 1993 for the latter gauging station.

The implications of the disaggregation of monthly data to a daily time-step were investigated by running the disaggregation procedure ten times to determine the sensitivity of the hydrological model to the random sequencing of rainfall events within each month. The Nash-Sutcliffe coefficient for Pakse varied by less than 0.05 between the original run and the mean of the ten subsequent runs. Very similar 30-year monthly mean flows were obtained suggesting that the model is not very sensitive to the disaggregation procedure.

4 Scenario results: prescribed warming using HadCM3

4.1 Changes in climate

Changes in temperature associated with prescribed warming of global mean temperature using the HadCM3 GCM are relatively uniform across the seven modelled sub-basins of the Mekong, with only the Lancang sub-basin experiencing slightly different changes. Temperatures increase linearly with increasing global mean temperature. The greatest warming in all basins occurs from November–April (e.g. 2.5 to 3.5 °C in the 2 °C scenario), with slightly weaker warming occurring in the May–October period

HESSD
7, 5991–6024, 2010

(e.g. 2.0 to 2.5 °C for the 2 °C scenario). The Lancang sub-basin has slightly more consistent year-round warming but a similar overall magnitude of increasing temperatures. Inter-seasonal and inter-basin patterns are the same for the 6 °C scenario, but with increased magnitude, such that warming is between 7.5 and 10.5 °C for November–April and varies between 6.0 and 7.5 °C for May–October.

On an annual basis, the HadCM3 precipitation climate change signal (relative to the UDel baseline) is small (≤1%) for most sub-basins, with the exception of the three northerly sub-basins, all of which show increases (for the 2 °C scenario, Lancang: 10%; Nam Ou: 11%; Nam Ngum: 5%). In contrast, the monthly precipitation signal is highly variable, but demonstrates linear rates of change with increasing global mean temperature. The two most northerly sub-basins, Lancang and Nam Ou, show increasing precipitation for nearly all months; April is the only month showing notable decreases (up to 16% decrease for the 2 °C scenario, 40% for the 6 °C scenario). Increases of approximately 20% for the 2 °C scenario (60% for the 6 °C scenario) occur for both basins in February, May, September and October. The other sub-basins show a more variable intra-annual signal, with most showing decreases from October–April (by up to 50% for 2 °C; 70% for 6 °C) and July–August (up to 8% for 2 °C; 20% for 6 °C), and increases from May–June (up to 17% for 2 °C; 60% for 6 °C).

4.2 Changes in river flow

Results from the scenarios of prescribed increases in global mean temperature from 0.5 to 6 °C using the HadCM3 GCM generally show small decreases in annual runoff at Pakse with increasing global mean temperature (Table 1). However, unlike the changes in temperature and precipitation, modifications to river flow do not occur at a linear rate for either the mean discharge or the Q5 and Q95 flows (i.e. the discharges exceeded 5% and 95% of the time, respectively). Furthermore, high and low flows change in different directions, with low flows generally increasing, and high flows generally decreasing. Reductions from the Pakse baseline mean annual flow vary between 0.2 to 5.4%, but with little apparent link to the magnitude of global temperature change; the

HESSD
7, 5991–6024, 2010

smallest annual change occurs in the 6 °C scenario whereas the largest arises in the 1.5 °C scenario. The 4 °C scenario is somewhat of an outlier with a 4.5% increase in mean annual runoff from the 1961–1990 baseline.

Relatively small changes in the annual mean runoff at Pakse are projected under increases in global mean temperature of up to 6 °C but more substantial changes occur at Q5 and Q95, reaching −11.4% and +26.7%, respectively (Table 1). Large changes also occur in monthly discharge (Fig. 4a). River flow during August and September (the months of annual peak flow) decreases on average by 0.2 and 9.8% (respectively) for the 2 °C scenario, with changes of +2.4% and −16.0% for the 6 °C scenario. Although discharge decreases in most months, the largest monthly changes involve increases and occur in June (+27.0% for 2 °C; +55.6% for 4 °C, and +40.1% for the 6 °C scenario). These contrasting trends result because whilst increases in temperature occur for sub-basins in all months of the year, changes in precipitation vary in direction (both from sub-basin to sub-basin and month to month within sub-basins). The interaction of these contrasting trends and their impacts on monthly river flow provides partial explanation for the absence of a progressive linear trend in annual runoff as global mean temperature increases.

Further explanation for the absence of a progressive linear trend in annual runoff can be provided by considering the role of temperature, and specifically the balance between snow storage and release in the upper Mekong Basin and increasing PET throughout the basin. In contrast to the overall Mekong response, the Lancang sub-basin (Chiang-Saen gauging station) shows a near-linear increase in annual runoff from the 0.5 (+1.4%) to 6 °C (+15.3%) scenarios. Increasing annual runoff in the Lancang sub-basin is driven by increasing early and late season discharge, although counter-balanced by decreasing peak season discharge (Fig. 4b). The early season increases at Lancang are thought to be a result of higher temperatures and, in turn, enhanced snow-melt earlier in the year. This is demonstrated by the division of the river flow climate change signal into that attributable to temperature and precipitation (by holding temperature constant and varying precipitation, and vice versa) (Fig. 5).

HESSD
7, 5991–6024, 2010

This shows that with increasing temperature and unchanged precipitation, early season river flow increases, indicating the role of enhanced snowmelt and/or an increasing rain: snow ratio.

Increasing river flow in the Lancang sub-basin is likely to be responsible for the non-linear response of Pakse river flow to increasing temperatures (seen also in the Pakse temperature only climate change signal: Fig. 5a). The peak in the combined Pakse 4 °C scenario is therefore thought to be the result of the combination of increasing Lancang discharge (from the higher rain:snow ratio and greater snowmelt) and seasonal changes in precipitation across the Mekong Basin against the counterbalance of increasing PET throughout the basin.

5 Scenario results: 2 °C warming across seven GCMs

5.1 Changes in climate

The 2 °C prescribed warming scenarios from the seven different GCMs show contrasting changes in climate over the Mekong Basin. For temperature, all GCMs show increases of close to 2 °C, but with variation between GCMs in the monthly patterns of rising temperatures. For example, the CCCMA, HadGEM1 and NCAR GCMs show a relatively constant temperature climate change signal throughout the year for most sub-basins; the CSIRO and MPI GCMs have a distinct peak in April and the HadCM3 in February whereas the IPSL GCM has a broad peak in temperature rise from March–June. Also of note is the difference in the temperature signal over the Lancang sub-basin compared to the other sub-basins. For all GCMs except HadCM3 the temperature increase in the Lancang sub-basin is much greater than for the other sub-basins between January and April (for HadCM3 the Lancang temperature signal is weaker than for other basins during these four months).

Differences in the precipitation climate change signal between GCMs are far greater than for temperature, with little consistency in the magnitude, direction or seasonality

HESSD
7, 5991–6024, 2010

of change, or the level of similarity between sub-basins. At the annual level for the entire Mekong Basin, the CCCMA, HadCM3, MPI and NCAR GCMs show increasing precipitation (by between 3–10%) whereas the CSIRO, HadGEM1 and IPSL GCMs show decreases in precipitation of 3, 2 and 1%, respectively. Increasing (decreasing) annual precipitation is consistent across all sub-basins for the CCCMA, MPI and NCAR (CSIRO) GCMs. For the other GCMs, the increase in annual precipitation for the northerly sub-basins in the HadCM3 scenarios was noted previously. HadGEM1 also shows increases of 6% and 1% for the Lancang and Nam Ou basins, respectively, but decreasing annual precipitation for the other basins (peaking at 5% in the Chi and Mun basins). In contrast to the two Hadley Centre GCMs, IPSL shows decreasing precipitation for the three northerly basins, peaking at 5% for Lancang and Nam Ou, together with small ($<1.5\%$) increases in Chi-Mun and Mekong 2 precipitation. Inter-seasonal patterns of change range from unimodal (maximum decreases in January–March and peak increase in September: CSIRO, IPSL) to bimodal patterns of varying strengths (with peak increases around April and September, and decreases in June–July and December–January: CCCMA, NCAR, HadCM3, HadGEM1, MPI).

5.2 Changes in river flow

Projected changes in Pakse discharge show substantial disparities between GCMs with little consistency in either the magnitude or direction of change, for annual or seasonal mean discharge, or high and low flows (Table 2, Fig. 6a). There is no particular clustering of GCMs so it is not possible to label any GCM as a particular outlier, especially given that these seven GCMs are drawn from a larger population of 23 CMIP-3 GCMs (Meehl et al., 2007). The same is true for Ubon (Chi-Mun discharge). However, whilst substantial differences between GCMs also occur in the Lancang sub-basin (Chiang-Saen gauging station), results for all seven GCMs show increasing river flow from April–June, and decreasing flow in July and August (Fig. 6b).

Results from running the model with scenario precipitation and baseline temperature (and vice versa) show that it is inter-GCM differences in scenario precipitation that are

CC BY

the primary cause of variation in the overall climate change signal in Mekong (Pakse) discharge (Fig. 7a and b). The temperature-only climate signal in mean monthly discharge is very consistent between all seven GCMs. In contrast, the precipitation-only climate change signal shows both increases and decreases in monthly discharge. Similar results are found for the Lancang (Chiang-Saen) sub-basin (Fig. 7c and d), indicating that the April–June rising trend in river flow is a temperature rather than precipitation driven trend. As with the HadCM3 results, these results demonstrate the likely importance of snowmelt and the snow: rain ratio of precipitation for Lancang river flow.

6 Uncertainty in model parameterisation

In the absence of quantitative estimates of uncertainty associated with model parameterisation from an autocalibration routine, a manual assessment was made to provide an indication of model parameterisation uncertainty. This was undertaken by varying the most sensitive parameters in the hydrological model. Seven parameters were selected based on the results from initial manual model calibration and parameter sensitivity rankings provided by Kite (2008). The parameters investigated were the retention constants and capacities of the fast and slow soil stores, and coefficients for evaporation, field capacity and Manning's roughness.

Each parameter was varied by ±10% from the calibrated value and the model rerun with baseline climate data. The model was then run using the same perturbed parameter set with scenario climate data (the HadCM3 2 °C prescribed warming was used as an exemplar scenario). The difference between the reference and perturbed runs was then compared between baseline and scenario situations. If the difference between the reference and perturbed runs is greater for the scenario than the baseline, then model parameterisation may be a cause of further uncertainty in climate change projections (and vice versa).

Results of the uncertainty analysis indicate that model parameterisation generally imparts little uncertainty to the climate change projections relative to that generated by

HESSD
7, 5991–6024, 2010

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

differences in GCM precipitation (Fig. 8). However, it should be noted that these findings are based on the HadCM3 2 °C prescribed warming scenario only. Differences in the reference-perturbed percent anomaly between baseline and HadCM3 2 °C scenario runs are generally less than ±2%, with the most sensitive parameters relating to soil water capacity and the Manning's roughness coefficient of the river channel.

7 Discussion

This paper has presented an assessment of future availability of freshwater resources within the Mekong Basin as a result of climate change, combined with an evaluation of the range of uncertainty in this assessment due to climate sensitivity, choice of GCM and hydrological model parameterisation. Our results are comparable to those of previous studies of the Mekong (e.g., Kiem et al., 2008; Ishidaira et al., 2008) but we show the overwhelming dependence on the GCM used for projections of future availability of freshwater resources. Single-GCM evaluations of climate change impacts are therefore likely to be wholly inadequate (and potentially misleading) as a basis for climate change impacts studies for this major river basin.

Despite the substantial uncertainty associated with the choice of GCM, a number of additional important issues are raised by these results which are both specific to the Mekong, and of more general relevance to the assessment of climate change impacts on water resources. For example, results show that the GCM temperature signal for river flow is far more consistent than the precipitation signal (see Kingston and Taylor, 2010). As such, some confidence can be placed in the finding that flows in the upper Mekong Basin will increase in the first half of the calendar year due to enhanced melting of snow and ice since this result is consistent across all GCMs and all scenarios examined. The importance of snow accumulation and melt dynamics has previously been demonstrated for the Mekong Basin (Kiem et al., 2005). Increasing temperature can also be expected to lead to increased evaporation throughout the basin.

HESSD
7, 5991–6024, 2010

The results also demonstrate that when averaged over large areas such as the Mekong or even its sub-basins, neither high, low, nor mean annual river flow may respond in a linear way to increasing temperatures. This concurs with the findings of Ishidaira et al. (2008). This is thought to be a consequence of contrasting response to increased temperature across the Mekong Basin (earlier snowmelt versus increased evapotranspiration), complicated by seasonally variable changes in precipitation. Two further important issues can also be highlighted: firstly, the potential for thresholds of climate change impacts on water resources (possibly 4 °C here), and secondly, the importance of investigating changing water resources on an intra-annual basis as it is a combination of linear changes in monthly river flow that give rise to the non-linear annual response. In large basins that cross climatic zones, such as the Mekong, further complication is added by the possibility of different climate trends and changes in the relative importance of different hydrological processes in different sections of the basin. These factors make it difficult to ascribe simple attributions to downstream trends in discharge.

Results of this study demonstrate the importance of understanding the roles and interaction of changes in temperature and the implications of this for both PET and storage of precipitation as snow or ice. Together with changing magnitudes and seasonality of precipitation, these temperature driven changes have important implications for river flow. This is further complicated by the time taken for water to pass through the continental-scale Mekong River Basin. Although the role of PET is key to changes in the hydrological behaviour of the Mekong, there remains substantial uncertainty regarding estimation of both baseline and scenario PET. Whilst the relative advantages and disadvantages of many different methods of estimating historical PET from meteorological data have been widely considered (e.g., Vorosmarty et al., 1998; Lu et al., 2005), relatively little attention has been given to how representative different PET methods remain when transferred from baseline to scenario climatology. Indeed, recent work (Kingston et al., 2009; Kingston and Taylor, 2010) has shown that different methods of estimating PET can produce markedly different climate change signals, suggesting that this is an area for further research.

Whilst further uncertainty in the climate change signal for the Mekong River Basin is likely to arise from the parameterisation and structure of the hydrological model used, the findings presented here indicate that such uncertainty is much smaller than that associated with choice of GCM, climate sensitivity, and possibly observed baseline data. Despite this, it should be noted that this paper has only conducted an initial (and subjective) assessment of model parameter uncertainty. These findings should therefore be taken as indicative rather than definitive. Future work will aim to treat model uncertainty in a more objective probabilistic manner (for example, by using autocalibration routines).

8 Conclusions

A number of important findings have resulted from this study of climate change impacts on the hydrology of the Mekong River Basin. Firstly, and most importantly, it has been shown that projections of hydrological change in the basin are highly dependent upon the direction of future variation in precipitation. The considerable differences in precipitation projections produced by different GCMs emphasise the need for multi-model evaluations of climate change impacts. It is notable that this is still the case even in a region highlighted by the IPCC 4th Assessment Report as having a relatively consistent precipitation climate change signal.

Despite such uncertainty, it has been demonstrated that useful information can still be obtained, for example by focussing on future changes in discharge associated with changing temperature, as temperature is consistently simulated to rise across the Mekong River Basin by all seven GCMs. Accordingly, this study has indicated projections of earlier and reduced magnitude snowmelt-related seasonal flow peak in the upper Mekong Basin are robust even in the presence of substantial uncertainty in future precipitation projections. It is likely that such changes (particularly in high and

CC BY

low flows) will have important implications for both the ecological and anthropogenic development of the Mekong River Basin.

Acknowledgements. This work was supported by a grant from the UK Natural and Environmental Research Council (NERC) awarded to the Department of Geography, University College London (Taylor, Todd, Thompson) under the Quantifying and Understanding the Earth System (QUEST) programme (Ref. NE/E001890/1). Figure 1 was redrawn by Tracy Connolly (University of Otago).

References

Apaydin, H., Anli, A. S., and Ozturk, A.: The temporal transferability of calibrated parameters of a hydrological model, Ecol. Model., 195(3–4), 307–317, 2006.

Armstrong, R. N. and Martz, L. W.: Effects of reduced land cover detail on hydrological model response, Hydrol. Process., 22, 2395–2409, 2008.

Arnell, N. W.: Effects of IPCC SRES* emissions scenarios on river runoff: a global perspective, Hydrol. Earth Syst. Sci., 7, 619–641, doi:10.5194/hess-7-619-2003, 2003.

Arnell, N. W. and Osborn, T.: Interfacing climate and impacts models in integrated assessment modelling, Tyndall Centre for Climate Change Research Technical Report 52, 2006.

Bates, B. C., Kundzewicz, Z. W., Wu, S. and Palutikof, J. P. (Eds.): Climate Change and Water, Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, Switzerland, 2008.

Christensen, J. H., Hewitson, B., Busuioc, A., et al.: Regional climate projections, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., et al., Cambridge University Press, UK, 849–926, 2007.

Costa-Cabral, M. C., Richey, J. E., Goteti, G., Lettenmaier, D. P., Feldkötter, C., and Snidvongs, A.: Landscape structure and use, climate, and water movement in the Mekong River basin, Hydrol. Process., 22, 1731–1764, 2008.

Food and Agricultural Organisation of the United Nations (FAO): FAO-UNESCO Soil Map of the World: Revised Legend, World Soil Resources Report 60, FAO, Rome, Italy, 1990.

Hapuarachchi, H. A. P., Takeuchi, K., Zhou, M. C., Kiem, A. S., Georgievski, M., Magome, J.,

HESSD

7, 5991–6024, 2010

Uncertainty in projections for the Mekong

D. G. Kingston et al.

and Ishidaira, H.: Investigation of the Mekong River basin hydrology for 1980–2000 using the YHyM, Hydrol. Process., 22, 1246–1256, 2008.
Henriksen, H. J., Troldborg, L., Højberg, A. J., and Refsgaard, J. C.: Assessment of exploitable groundwater resources of Denmark by use of ensemble resource indicators and a numerical groundwater – surface water model, J. Hydrol., 348, 224–240, 2008
Hughes, D. A., Kingston, D. G., and Todd, M. C.: Uncertainty in water resources availability in the Okavango River Basin as a result of climate change, Hydrol. Earth Syst. Sci. Discuss., 7, 5737–5768, doi:10.5194/hessd-7-5737-2010, 2010.
Hulme, M., Wigley, T. M. L., Barrow, E. M., Raper, S. C. B., Centella, A., Smith, S. J., and Chipanshi, A. C.: Using a Climate Scenario Generator for Vulnerability and Adaptation Assessments: MAGICC and SCENGEN Version 2.4 Workbook, Climatic Research Unit, Norwich UK, 52 pp., 2000.
Ishidaira, H., Ishikawa, Y., Funada, S., and Takeuchi, K.: Estimating the evolution of vegetation cover and its hydrological impact in the Mekong River Basin in the 21st Century, Hydrol. Process., 22, 1395–1405, 2008.
Jain, S. K., Kumar, N., Ahmad, T., and Kite, G. W.: SLURP model and GIS for estimation of runoff in a part of Satluj catchment, India, Hydrolog. Sci. J., 43(6), 875–884, 1998.
Jayawardene, A. W. and Mahanama, S. P. P.: Meso-scale hydrological modelling: application to Mekong and Chao Phraya basins, J. Hydrol. Eng., 7, 12–26, 2002.
Kiem, A. S., Geogievsky, M. V., Hapaurachchi, H. P., Ishidaira, H., and Takeuchi, K.: Relationship between ENSO and snow covered area in the Mekong and Yellow River basins, in: Regional Hydrological Impacts of Climate Change – Hydroclimatic Variability, edited by: Franks, S. W., Wagener, T., Bøgh, E., et al., IAHS Publ. 296, Wallingford, UK, 255–264, 2005.
Kiem, A. S., Ishidaira, H., Hapuarachchi, H. P., Zhou, M. C., Hirabayahi, Y., and Takeuchi, K.: Future hydroclimatology of the Mekong River basin simulated useing the high-resolution Japan Meteorological Agency (JMA) AGCM, Hydrol. Process., 22, 1382–1394, 2008.
Kim, B. S., Kim, H. S., Seoh, B. H., and Kim, N. W.: Impact of climate change on water resources in Yongdam Dam Basin, Korea, Stoch. Env. Res. Risk A., 21(4), 355–373, 2007.
Kingston, D. G. and Taylor, R. G.: Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda, Hydrol. Earth Syst. Sci., 14, 1297–1308, doi:10.5194/hess-14-1297-2010, 2010.
Kingston, D. G., Todd, M. C., Taylor, R. G., and Thompson, J. R.: Uncertainty in the

HESSD
7, 5991–6024, 2010

Uncertainty in projections for the Mekong

D. G. Kingston et al.

potential evapotranspiration climate change signal, Geophys. Res. Lett., 36, L20403, doi:10.1029/2009GL040267, 2009.
Kite, G.: The SLURP model, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resources Publications, Colorado, USA, 521–562, 1995.
Kite, G.: Modelling the Mekong: hydrological simulation for environmental impact studies, J. Hydrol., 253, 1–13, 2001.
Kite, G: Manual for the SLURP hydrological model version 12.7, HydroLogic-Solutions, 2008.
Legates, D. R. and Willmott, C. J.: Mean seasonal and spatial variability in gauge-corrected, global precipitation, Int. J. Climatol., 10, 111–127, 1990.
Li, S. J. and He, D. M.: Water level response to hydropower development in the upper Mekong River, Ambio, 37, 170–177, 2008.
Lu, J. B., Sun, G., McNulty, S. G., and Amataya, D. M.: A comparison of six potential evapotranspiration methods for regional use in the Southeastern United States, J. Am. Water Resour. As., 41, 621–633, 2005.
Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: THE WCRP CMIP3 Multimodel Dataset: a new era in climate change research, B. Am. Meteorol. Soc., 88, 1383–1394, 2007.
Mekong River Commission (MRC): State of the basin report: 2003, Mekong River Commission, Phomh Penh, ISSN: 1728:3248, 2003.
Mileham, L., Taylor, R. G., Thompson, J. R., Todd, M. C., and Tindimugaya, C.: Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in Equatorial Africa, J. Hydrol., 359, 46–58, 2008.
Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693–712, 2005.
New, M., Hulme, M., and Jones, P. D.: Representing twentieth century space-time climate variability. Part I: Development of a 1961–1990 mean monthly terrestrial climatology, J. Climate, 12, 829–856, 1999.
Park, G. A., Shin, H. J., Lee, M. S., Hong, W. Y., and Kim, S. J.: Future potential impacts of climate change on agricultural watershed hydrology and the adaptation strategy of paddy rice irrigation reservoir by release control, Paddy Water Env., 7(4), 271–282, 2009.
Randall, D. A., Wood, R. A., Bony, R., et al.: Climate models and their evaluation, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the

HESSD
7, 5991–6024, 2010

Uncertainty in projections for the Mekong

D. G. Kingston et al.

Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., et al., 589–662, Cambridge Univ. Press, Cambridge, UK, 2007.

Stone, R.: Along with power, questions flow at Laos's new dam, Science, 328, 414–415, 2010.

Su, M., Stolte, W. J., and van der Kamp, G.: Modelling Canadian prairie wetland hydrology using a semi-distributed streamflow model, Hydrol. Process., 14(14), 2405–2422, 2000.

Todd, M. C., Taylor, R. G., Osborn, T. Kingston, D., Arnell, N., and Gosling, S.: Quantifying the impact of climate change on water resources at the basin scale on five continents – a unified approach, Hydrol. Earth Syst. Sci., submitted, 2010.

Västilä, K., Kummu, M., Sangmanee, C., and Chinvanno, S.: Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains, J. Water Clim. Change, 1, 67–86, 2010.

Viney, N. R., Bormann, H., Breuer, L., Bronstert, A., Croke, B. F. W., Frede, H., Graff, T., Hubrechts, L., Huisman, J. A., Jakeman, A. J., Kite, G. W., Lanini, J., Leavesley, G., Lettenmaier, D. P., Lindstrom, G., Seibert, J., Sivapalan, M., and Willems, P.: Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) – II: Ensemble combinations and predictions, Adv. Water Resour., 32(2), 147–158, 2009.

Vörösmarty, C. J., Federer, C. A., and Schloss, A. L.: Potential evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modelling, J. Hydrol., 207, 147–169, 1998.

Woo, M. K., Long, T. Y., and Thorne, R.: Simulating monthly streamflow for the Upper Changjiang, China, under climatic change scenarios, Hydrol. Sci. J., 54, 596–605, 2009.

Xu, H., Taylor, R. G., Kingston, D. G., Jiang, T., Thompson, J. R., and Todd, M.: Hydrological modelling of the River Xiangxi using SWAT 2005: a comparison of model parameterizations using station and gridded meteorological observations, Quatern. Int., in press, doi:10.1016/j.quaint.2009.11.037, 2010.

CC BY

HESSD
7, 5991–6024, 2010

D. G. Kingston et al.

CC BY

Table 1. Percent change in Pakse (Mekong 2) annual mean, Q5 and Q95 discharges for 0.5–6 °C increases in global mean temperature using HadCM3.

Scenario	Q5	Mean	Q95
0.5 °C	−7.7	−3.7	2.8
1.0 °C	−3.6	−0.7	−0.6
1.5 °C	−8.6	−4.7	3.2
2.0 °C	−7.6	−1.6	0.4
2.5 °C	−11.3	−5.4	10.4
3.0 °C	−11.3	−2.6	8.9
4.0 °C	−4.4	4.5	24.0
5.0 °C	−9.9	−2.0	26.2
6.0 °C	−11.4	−0.2	26.7

HESSD
7, 5991–6024, 2010

CC BY

Table 2. Percent change in Pakse (Mekong 2) annual mean, Q5 and Q95 discharges for 2 °C increase in global mean temperature using seven GCMs.

GCM	Q5	Mean	Q95
CCCMA	1.8	5.7	8.0
CSIRO	−18.0	−17.8	−13.4
HadCM3	−7.6	−1.6	0.4
HadGEM1	−18.1	6.5	−1.9
IPSL	−5.1	−10.2	−16.2
MPI	5.9	−9.5	−3.0
NCAR	6.3	3.0	5.9

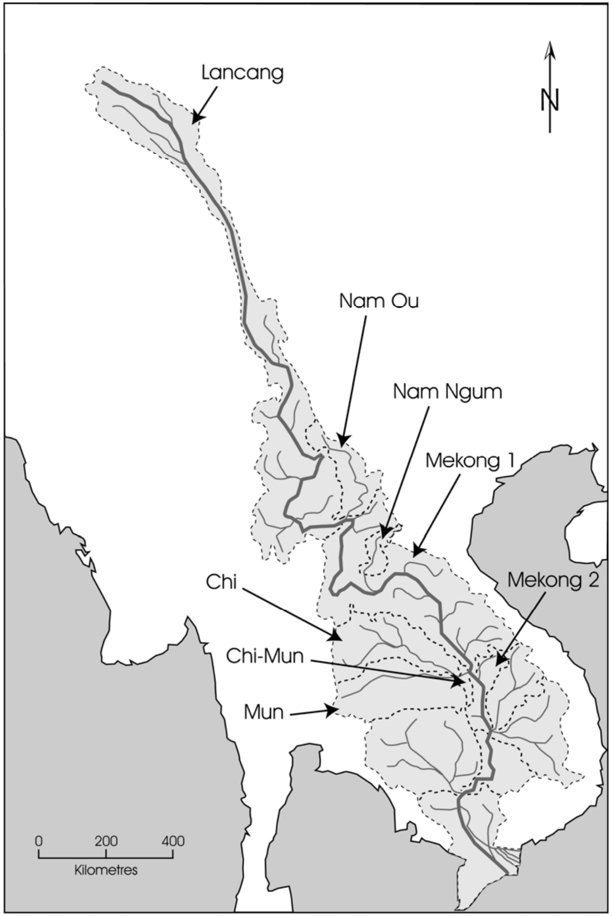

Fig. 1. The Mekong River Basin and sub-basins defined by Kite (2001). Note: only the sub-basins modelled in the current study are labelled.

HESSD
7, 5991–6024, 2010

Uncertainty in projections for the Mekong

D. G. Kingston et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

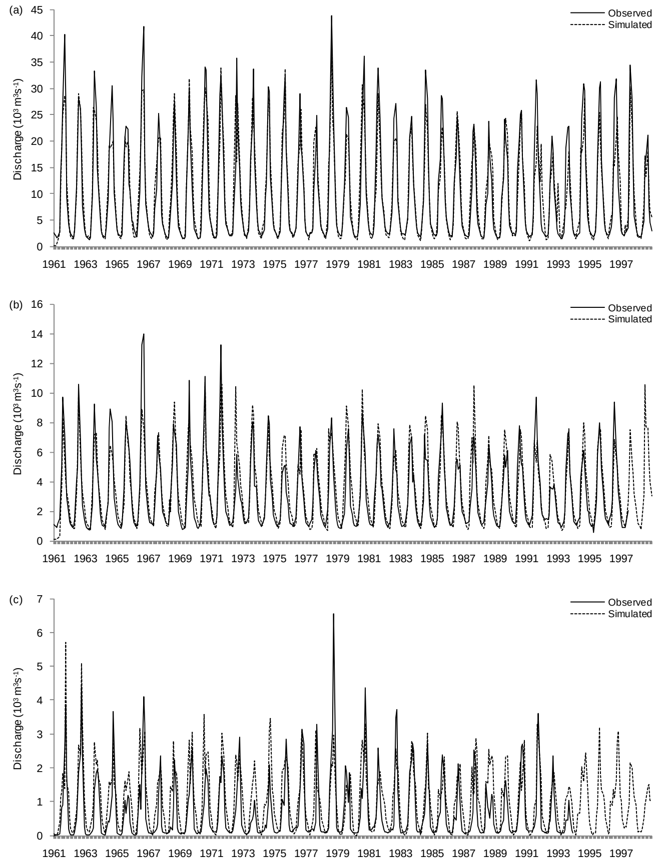

Fig. 2. Observed and simulated monthly discharges: **(a)** Mekong at Pakse (Mekong 2), **(b)** Lancang sub-catchment at Chiang-Saen, **(c)** Chi-Mun sub-catchment at Ubon (note varying *y*-axis scales).

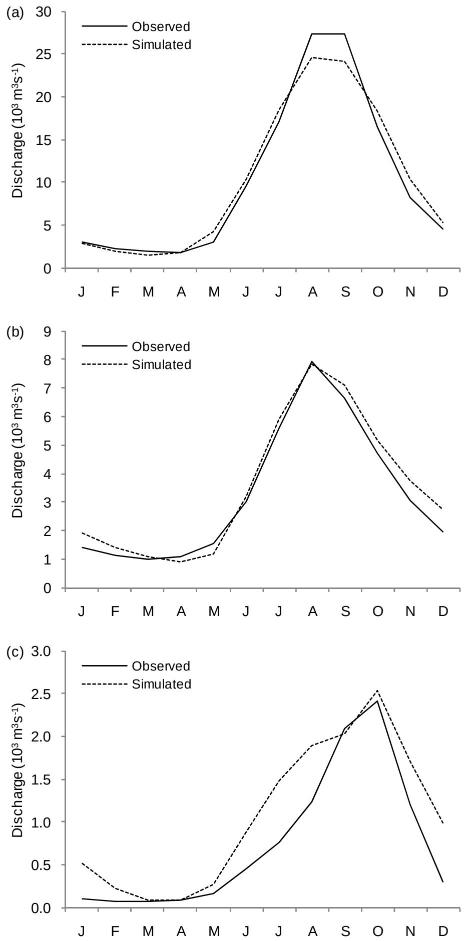

Fig. 3. Observed and simulated mean monthly discharges (1961–1990): **(a)** Mekong at Pakse (Mekong 2), **(b)** Lancang sub-catchment at Chiang-Saen, **(c)** Chi-Mun sub-catchment at Ubon (note varying *y*-axis scales).

HESSD
7, 5991–6024, 2010

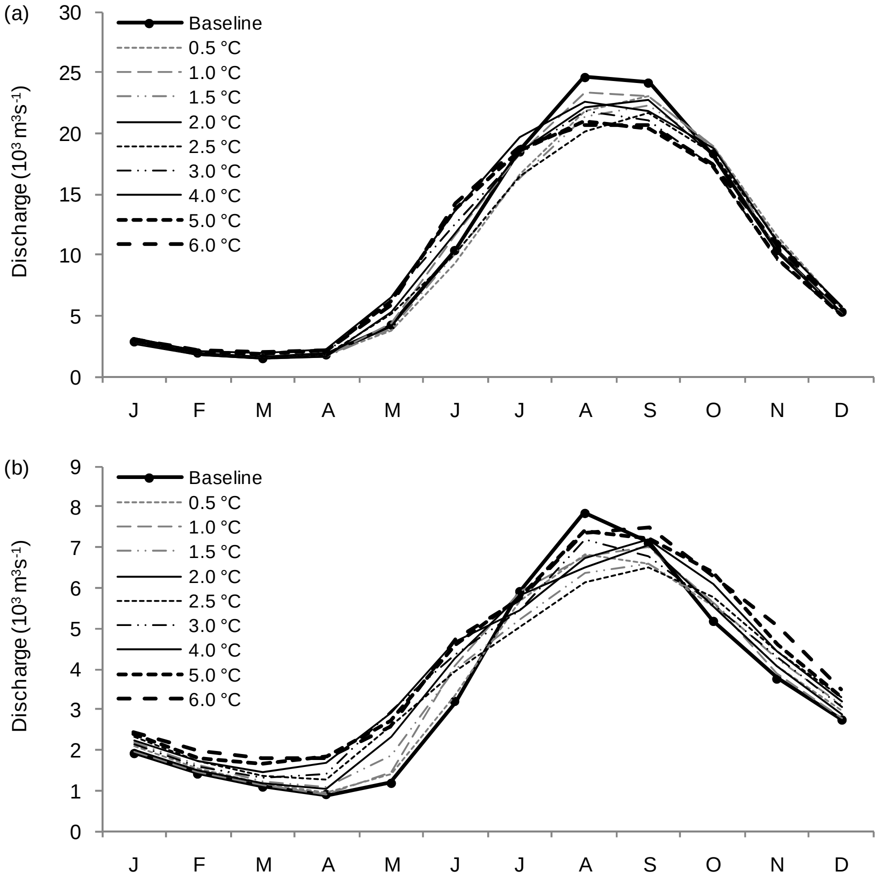

Fig. 4. HadCM3 climate change signal for 0.5–6 °C increases in global mean temperature: **(a)** mean monthly discharge of the Mekong at Pakse (Mekong 2), **(b)** mean monthly discharge of the Lancang sub-catchment at Chiang-Saen.

HESSD
7, 5991–6024, 2010

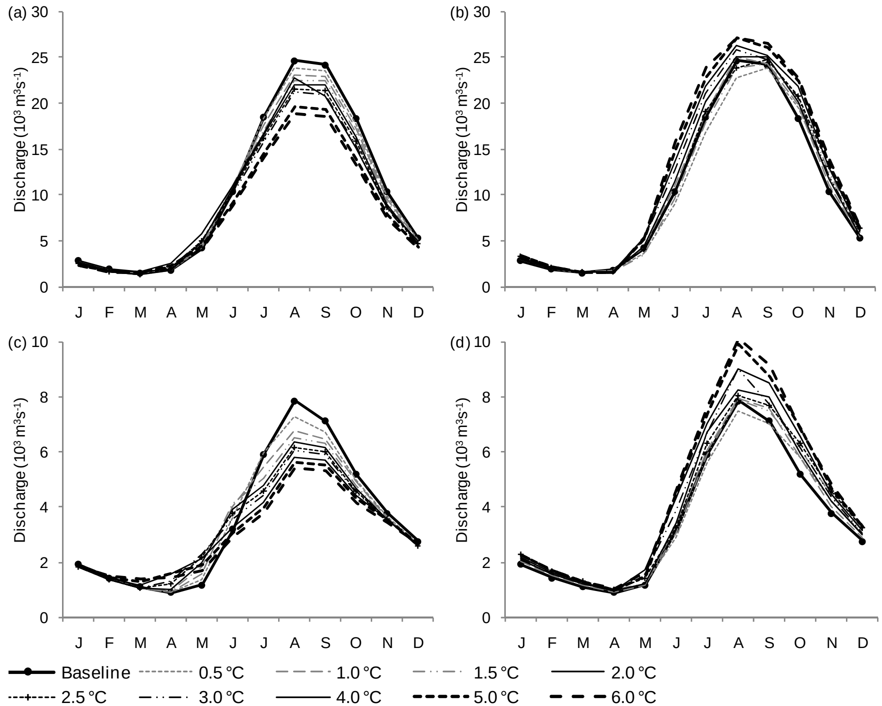

Fig. 5. HadCM3 climate change signal for 0.5–6 °C increases in global mean temperature for the Mekong at Pakse (Mekong 2): **(a)** temperature only, **(b)** precipitation only; and Lancang at Chiang-Saen: **(c)** temperature only, **(d)** precipitation only.

HESSD
7, 5991–6024, 2010

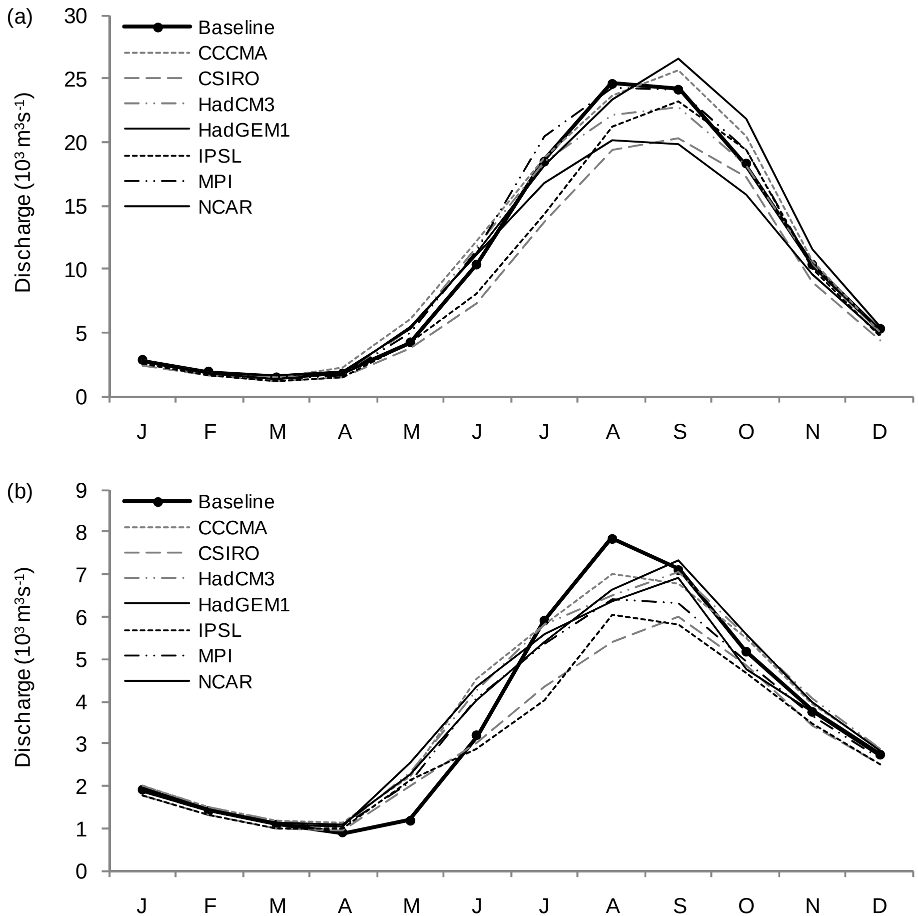

Fig. 6. 2 °C climate change signal across seven GCMs: **(a)** mean monthly discharge of the Mekong at Pakse (Mekong 2), **(b)** mean monthly discharge of the Lancang sub-catchment at Chiang-Saen.

HESSD
7, 5991–6024, 2010

Uncertainty in projections for the Mekong

D. G. Kingston et al.

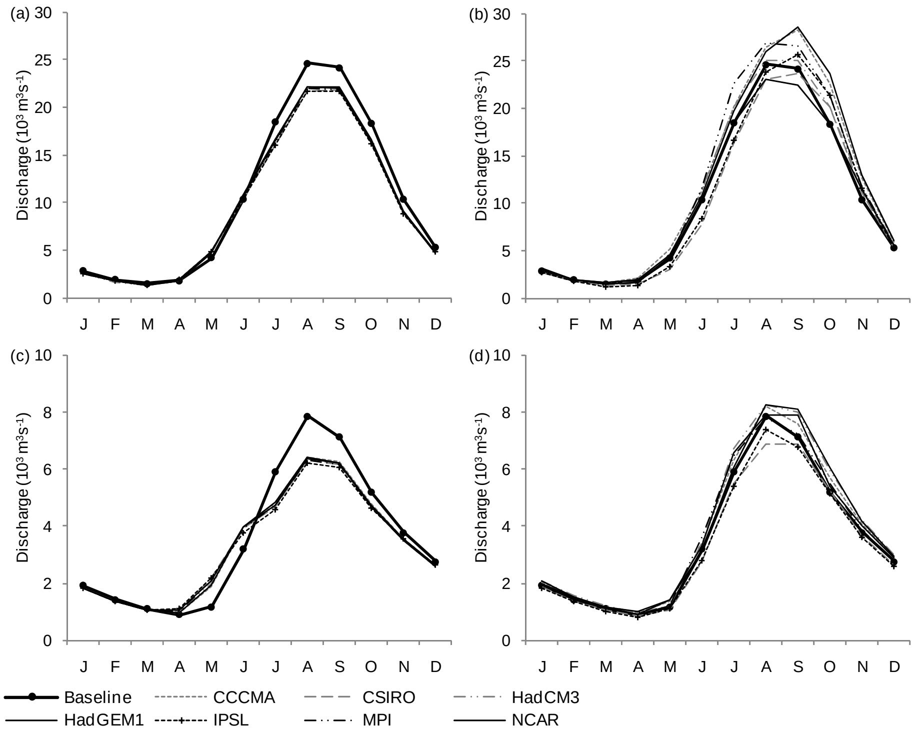

Fig. 7. 2˚C climate change signal across seven GCMs for the Mekong at Pakse (Mekong 2): **(a)** temperature only, **(b)** precipitation only; and Lancang at Chiang-Saen: **(c)** temperature only, **(d)** precipitation only.

CC BY

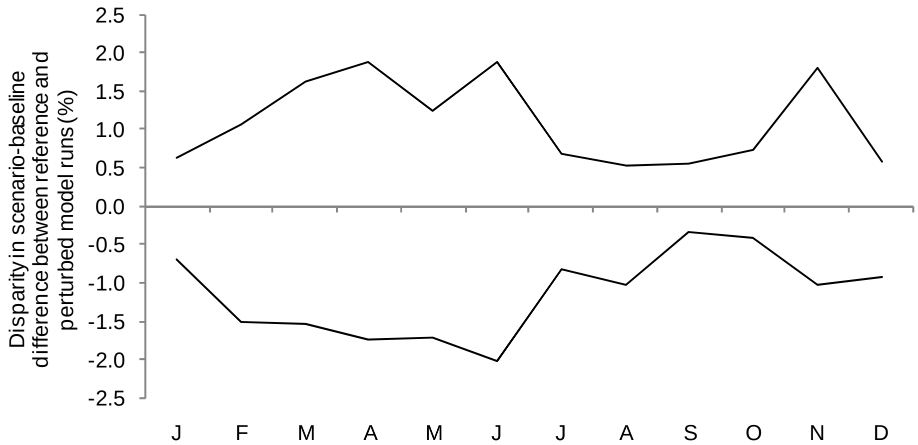

Fig. 8. Model parameter uncertainty for HadCM3 2 °C scenario: maximum extent of the disparity between the scenario-baseline difference in the perturbed parameter versus reference model runs.

HESSD
7, 5991–6024, 2010

CC BY