Hydrol. Earth Syst. Sci. Discuss., 12, 11651–11687, 2015
www.hydrol-earth-syst-sci-discuss.net/12/11651/2015/
doi:10.5194/hessd-12-11651-2015

Hydrology and Earth System Sciences
Open Access
Discussions

# Mekong River flow and hydrological extremes under climate change

**L. P. Hoang[1], H. Lauri[2], M. Kummu[3], J. Koponen[2], M. T. H. van Vliet[1], I. Supit[1], R. Leemans[4], P. Kabat[1,5], and F. Ludwig[1]**

[1]Earth System Science group, Wageningen University, P.O. Box 47,
6700 AA Wageningen, the Netherlands
[2]EIA Finland Ltd., Sinimäentie 10B, 02630 Espoo, Finland
[3]Water & Development Research Group, Aalto University, P.O. Box 15200, Aalto, Finland
[4]Environmental Systems Analysis group, Wageningen University, P.O. Box 47,
6700 AA Wageningen, the Netherlands
[5]International Institute for Applied System Analysis, Schlossplatz 1, 2361 Laxenburg, Austria

Received: 16 October 2015 – Accepted: 31 October 2015 – Published: 10 November 2015

Correspondence to: L. P. Hoang (long.hoang@wur.nl)

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

## Abstract

Climate change poses critical threats to water related safety and sustainability in the Mekong River basin. Hydrological impact signals derived from CMIP3 climate change scenarios, however, are highly uncertain and largely ignore hydrological extremes. This paper provides one of the first hydrological impact assessments using the most recent CMIP5 climate change scenarios. Furthermore, we model and analyse changes in river flow regimes and hydrological extremes (i.e. high flow and low flow conditions). Similar to earlier CMIP3-based assessments, the hydrological cycle also intensifies in the CMIP5 climate change scenarios. The scenarios ensemble mean shows increases in both seasonal and annual river discharges (annual change between +5 and +16 %, depending on location). Despite the overall increasing trend, the individual scenarios show differences in the magnitude of discharge changes and, to a lesser extent, contrasting directional changes. We further found that extremely high flow events increase in both magnitude and frequency. Extremely low flows, on the other hand, are projected to occur less often under climate change. Higher low flows can help reducing dry season water shortage and controlling salinization in the downstream Mekong Delta. However, higher and more frequent peak discharges will exacerbate flood risk in the basin. The implications of climate change induced hydrological changes are critical and thus require special attention in climate change adaptation and disaster-risk reduction.

## 1 Introduction

The Mekong River basin is one of the most important transboundary rivers in Southeast Asia. Starting from the Tibetan Plateau, the 4800 km long river flows crosses six different countries, namely China, Myanmar, Laos PDR, Thailand, Cambodia and finally the Vietnamese Mekong River delta before draining into the South China Sea. The economies and societies along the Mekong are strongly linked to its abundant water resources (MRC, 2010). The most important river dependent economic sectors include agriculture, energy (i.e. hydropower production) and fishery (Västilä et al., 2010; MRC, 2011a; Ziv et al., 2012). Currently, the Mekong basin is home to about 70 million people and this population is expected to increase to 100 million by 2050 (Varis et al., 2012). Economic development has been accelerating rapidly over the last decades together with substantial increases in water resources use (Jacobs et al., 2002; Lebel et al., 2005; Piman et al., 2013). Both demographic and economic trends imply an increasing importance of water resources for future socio-economic developments (Pech and Sunada, 2008; Hoanh et al., 2010; Keskinen et al., 2010). Therefore, the issue of securing water safety and long-term sustainability is especially important in water resources management in this transboundary river basin.

Socio-economic developments in the Mekong River basin, however, are facing critical challenges relating to water resources, including hydrological changes caused by climate change (Keskinen et al., 2010; MRC, 2010; Västilä et al., 2010). Existing studies (e.g. Eastham et al., 2008; Hoanh et al., 2010; Västilä et al., 2010) suggest that climate change will alter the current hydrological regime and thus posing critical challenges for ecosystems and socio-economic developments. For instance, Västilä et al. (2010) and Hoanh et al. (2010) modelled the Mekong's flow regimes under several climate change scenarios and suggested a likely intensification of the hydrological cycle, resulting in increases in annual and seasonal river discharges. Consequently, they also suggest increasing flood risks during the wet season in the Cambodian and Vietnamese floodplain as a direct consequence of increasing river flow. Other studies (e.g. Lauri et al., 2012 and Kingston et al., 2011) also suggest possible discharge reduction in the dry season under some individual climate change scenarios.

Although a considerable number of studies about climate change impacts on the Mekong's hydrology exist, two major challenges in understanding hydrological responses to climate change remain. First, existing hydrological impact assessments for the Mekong basin prove highly uncertain. In particular, impact signals differ markedly in the magnitudes and even directions of changes across the individual global circulation models (GCMs) and climate change scenarios. Kingston et al. (2011) quantified uncertainties related to the choice of GCMs and climate change scenarios in projecting the Mekong's future hydrology. Their results for monthly river discharge change show a large range between −16 and +55 %. They also noted that hydrological changes under different GCMs and scenarios differ remarkably in magnitude and even in contrasting directions. Another study by Lauri et al. (2012) also reported a wide range of discharge change between −11 and +15 % during the rainy season and between −10 and +13 % during the dry season. Both studies noted the uncertainty in hydrological impact signals, which mainly associate with uncertainties in the climate change projection, especially precipitation changes. Given these uncertainties in climatic and hydrological changes, they all also stress the importance to use multiple GCMs and several scenarios (i.e. an ensemble approach) rather than relying on a single model or climate change projection. Notably, all earlier studies used the SRES emission scenarios (Nakicenovic et al., 2000), used for the third phase of the Climate Models Inter-comparison Project (CMIP3). These SRES scenarios, which only include non-intervention scenarios, have recently been replaced by the Representative Concentration Pathways (RCP) scenarios (van Vuuren et al., 2011; Stocker et al., 2013), resulting in a broader range of climate change. These most recent climate change scenarios (i.e. CMIP Phase 5 or CMIP5) are not yet routinely used to assess the hydrological impacts in the Mekong basin. In addition, the CMIP5 scenarios also exhibit important improvements, both in terms of the GCMs' technical development (Taylor et al., 2011; Knutti and Sedláček, 2013) and in the efficiency to reproduce the historic climate conditions (Shabehuh et al., 2015). These important improvements and updates are highly relevant and require to update the hydrological projections for the Mekong. In this study, we will do this update and reflect whether the CMIP3 uncertainties relating to the wide hydrological signal will be reduced as well.

Second, although hydrological extremes under future climatic change are in particular relevant for water management and climate change adaptation (Piman et al., 2013; Cosslett and Cosslett, 2014), very little insights have been gained on this topic so far in the Mekong. Previous studies typically analysed hydrological changes at monthly and seasonal timescales and less studies focused on changes in frequency and severity of extreme events (i.e. climate change induced floods and droughts). This knowledge gap also relates for the fact that uncertainties, especially those relating to future monsoon and precipitation changes, prevail the CMIP3 climate change projections. Given high level of policy-relevance and important improvements in CMIP5 climate change projections, future changes in extreme high and low river flows should be comprehensively assessed and made available to decision makers.

In this paper, we aim to address these knowledge gaps in understanding the Mekong's hydrology under climate change. A distributed hydrological model was setup and calibrated for the whole Mekong River (Sects. 2.2 and 3.1). We selected a set of 10 climate model experiments for five GCMs and two RCPs from the CMIP5 and performed a downscaling and bias-correction on the climate model output (Sect. 2.3). Future changes in precipitation and temperature (Sect. 3.2) and subsequently the Mekong's annual and monthly discharge changes were quantified (Sect. 3.3). In addition, we quantified changes in hydrological extremes, focusing on both extreme low and high flows (Sect. 3.4). We will also reflect on the robustness of the resulting hydrological signals by discussing the inherent uncertainties in our analysis and comparing our results with outcomes of studies based on the previous CMIP3 scenarios (Sect. 4).

## 2 Methodology

### 2.1 The Mekong River basin

The Mekong (Fig. 1) is an average-sized river basin compared to other major rivers of the world. Its total drainage area is about 795 000 km$^2$, distributed unevenly across six Southeast Asian countries (MRC, 2005). The river's annual discharge volume of 475 km$^3$, is considerably higher than similarly sized river basins. Despite its moderate area, the Mekong ranks tenth in terms of annual discharge volume (Dai and Trenberth, 2002). This implies that the basin receives higher precipitation amount, owing to its dominant tropical monsoon climate (Adamson et al., 2009; Renaud et al., 2012). Elevation in the basin ranges between above 5000 m in the Tibetan Plateau to only a few meters above sea level in the downstream river delta.

The Mekong's hydrological regime is largely driven by monsoonal activities, most importantly the South-West Monsoon and to a lesser extent the North-East Monsoon (Costa-Cabral et al., 2007; MRC, 2009; Delgado et al., 2012). The South-East Monsoon is dominant from May to September, whereas the North-East Monsoon is active from November to February. These monsoonal activities characterize the basin's hydrology into two hydrological seasons with distinctive flow characteristics. A substantially larger proportion of the annual flow is generated during the wet seasons (June–November). Depending on location, the wet season flow accounts for between 75 and 85 % of the total annual flow (calculated from MRC, 2005). Seasonal variation in river flow, especially the flood pulse occurring in the downstream deltas (i.e. the Tonle Sap Lake in Cambodia and the Mekong delta in Vietnam), supports a highly productive aquatic ecosystem and one of the world's major rice production area (Junk et al., 2006; Eastham et al., 2008; Hapuarachchi et al., 2008).

Hydrological extremes, including both high and low flows, increase safety risks and undermine economic productivity in the basin, especially in the low-lying river delta (MRC, 2005; Lamberts and Koponen, 2008). Extreme floods caused by intensive and wide-spread precipitation events result in vast inundation and thereby damaging crops, infrastructure and, in very extreme cases (e.g. flood events in 2000 and 2011), disrupting the whole downstream delta's functioning. The catastrophic flood in 2000 with an estimated total economic loss of over 200 million US Dollars (Cosslett and Cosslett, 2014) illustrates the possible severe flood damage in this area. Extreme low flows also affect agriculture production, which largely depends on surface water irrigation in many parts of the basin. Lack of inflow from upstream during the dry season also exacerbates the risk of salt water intrusion, affecting the downstream delta's ecosystems, domestic water supply and agricultural production (Smajgl et al., 2015).

## 2.2 Hydrological model

VMod (Lauri et al., 2006) is a distributed hydrological model using a square grid representation of river basins. This grid uses multiple raster layers containing data for flow direction, river network, soil and land use. The simulation process starts with interpolating climate input for each grid cell from climate input data. VMod requires minimally four daily climate forcing variables (i.e. maximum, minimum and average air temperatures, and precipitation). Climate forcing data is calculated for each grid cell using an inverse distance weighted interpolation. Potential evapotranspiration (PET) is calculated using the Hargreaves–Samani method (Hargraeves and Samani, 1982), where PET is calculated using daily maximum, minimum temperatures, latitude and calendar day of the year. The soil is simulated as two distinctive layers and after soil surface processes, runoff water is routed from cell to cell and finally into the river network. A detailed description of the VMod model‘s algorithms and equations is available in the model's manual (Lauri et al., 2006).

In this study, we used the modelling setup for the Mekong River basin from Lauri et al. (2012). This Mekong modelling setup was prepared from several soil, land use and elevation datasets, allowing for daily hydrological simulation at 5 km × 5 km spatial resolution. Soil data was prepared from the FAO soil map of the world (FAO, 2003). Soil data were prepared by first reclassifying the original data into eight classes and then aggregated to a 5 km × 5 km grid. Similarly, land use data was prepared by reclassifying the original Global Land Cover 2000 data (GLC2000, 2003) into nine classes and then aggregated to the model's grid. The flow direction data was prepared from the SRTM90 m elevations (Jarvis et al., 2008). The elevation data along the main river's branches was adjusted to force these branches into the proper flow direction. More detailed information on the model setup and its parameterization for the Mekong basin is available in Lauri et al. (2012).

We calibrated and validated the hydrological model against observed daily river discharges at seven gauging stations: Chiang Saen, Vientiane, Nakhon Phanom, Mukdahan, Pakse, Stung Treng and Kratie (Fig. 1). Observed discharge data was obtained from the Mekong River Commission's hydrological database (MRC, 2011b). Calibration and validation periods are 1981–1991 and 1991–2001, respectively. The hydrological model's performance was assessed using discharge plots and model performance indices. In particular, the daily river discharges plots and the flow duration curves (Vogel and Fennessey, 1995) were used to visually check the goodness of fit between observed and simulated data. Furthermore, the Nash–Sutcliffe efficiency NSE (Nash and Sutcliffe, 1970) and relative biases indices were used to quantify the model's performance during calibration and validation. The Nash–Sutcliffe efficiency ranges between $-\infty$ and 1, where values closer to 1 imply a better fit between observed and simulated time series. The model's over- and underestimation of total annual river discharge, high flow and low flow indices (i.e. Q5 and Q95, respectively) were assessed by calculating the relative biases. These Q5 (high flow) and Q95 (low flow) are commonly used indices in hydrological analyses, defined as the values that exceed the discharge time series data by 5 and 95 % of the time, respectively. The biases are calculated as simulated values divided by observed values under the same time period of interest.

We started the model calibration by using the initial parameterization from Lauri et al. (2012). Discharge simulation performance was further improved by adjusting several model's parameters. In particular, discharge amount and timing at key stations were calibrated to better match with observed data by changing the two soil layers' depth and their water storage capacities. Vertical and horizontal infiltration rates were also adjusted to further improve simulations of high flows and low flows. Lastly, snowmelt rate and temperature thresholds for snow precipitation and snowmelt were adjusted to improve model performance at the upper catchment above Chiang Saen (Northern Thailand). All parameter values were adjusted within the physically realistic range described in Lauri et al. (2006) and Sarkkula et al. (2010).

## 2.3 Climate data

We prepared climate data for the historic period (1971–2000) and the future period (2036–2065) using various datasets. The required four climate variables were prepared as input data to VMod model. Historic temperature data was prepared from the WATCH Forcing Data (Weedon et al., 2011), which is a global historic climate dataset for the 1958–2001 period produced from the 40 year ECMWF Re-Analysis (Uppala et al., 2005) and bias-corrected using the CRU-TS2.1 observed data (Mitchell and Jones, 2005). This dataset is widely used in various global and regional studies (e.g. van Vliet et al., 2013; Krysanova et al., 2014; Leng et al., 2015; Veldkamp et al., 2015). Precipitation data was extracted from the APHRODITE dataset (Yatagai et al., 2012), which is an observation-based precipitation dataset, developed from a high-density network of rain gages over Asia. This dataset has been evaluated as one of the best gridded precipitation datasets for hydrological modelling purpose in the Mekong basin (Lauri et al., 2014).

Climate change scenarios were prepared from the most recent CMIP5 climate projection. Since the regional climate model data of the Coordinated Regional Climate Downscaling Experiment – CORDEX (Giorgi and Gutowski, 2015) so far only covers one GCM for the Mekong region, we decided to use GCM projections as basis for this climate impact assessment. We therefore downscaled the GCM projections ourselves. Given the relatively large number of GCMs under CMIP5, we first did a model selection by reviewing literature on GCM performance. We selected those GCMs that better reproduce historic tropical temperature and precipitation conditions. For historic temperature simulations, Huang et al. (2014) assessed the CMIP5 models efficiency for the Mekong basin and suggested BCC-CSM1-1, CSIRO-MK3-6-0, HadGEM2-ES and MIROC-ESM-CHEM as the better-performing models. Shabehuh et al. (2015) evaluated the GCM's performance in simulating seasonal precipitation focusing on monsoonal activities for three major river basins in South and Southeast Asia, including the Mekong. They concluded that the MPI models, MIROC5 and CSIRO-Mk3-6-0,

CCSM4, CESM1-CAM5, GFDL-ESM2G, IPSL-CMA-MR, MIROC-ESM and MIROC-ESM-CHEM perform better than other GCMs in the assessment. Furthermore, we also consulted Sillmann's et al. (2013) model evaluation to represent climate extremes. They indicated that ACCESS-1.0, CCSM4, MPI models and HadGEM2-ES are amongst the better performing models. Based on these GCM evaluations, we selected five GCMs for this study (Table 1). For each GCM, we extracted climate data for two different RCPs, namely RCP4.5 and RCP8.5. The RCP4.5 is a medium to low scenario assuming a stabilization of radiative forcing to 4.5 $\mathrm{W\,m^{-2}}$ by 2100 (Thomson et al., 2011). The RCP8.5 is a high climate change scenario assuming a rising radiative forcing leading to 8.5 $\mathrm{W\,m^{-2}}$ by 2100 (Riahi et al., 2011). By selecting a mid-range and a high-end scenario, we expect to capture a reasonable range in climatic and hydrological projections for the Mekong basin. We did not consider RCP2.6, which is the only scenario complying the internationally agreed 2 °C warming projection, since we do not think that this is a realistic target, given the current pace of greenhouse gases emissions.

Since the GCMs' spatial resolution is generally too coarse for a basin-scale study, we re-gridded the climate data to a $0.5^\circ \times 0.5^\circ$ grid using bilinear interpolation. Subsequently, the data is subjected to a statistical bias-correction, using the method developed by Piani et al. (2010) to correct biases in the GCM simulations. This bias-correction is done by developing transfer functions, which match the GCM historic (1959–2000) data's monthly statistics to an independent, observed climatology. We used the WATCH Forcing Data and APHRODITE as independent datasets. The developed transfer functions were then applied on the future climate data to correct the biases in the GCM's future climate projection. Detailed information on the bias-correction method is available in Piani et al. (2010).

### 2.4 Analysing hydrological changes

We employed several techniques to analyse different aspects of hydrological changes. First, annual and monthly discharges' statistics were calculated to understand changes in the river's flow regime. Second, we calculated the Q5 and Q95 to analyse changes in high flow and low flow conditions, respectively. Lastly, we fitted discharge data to suitable extreme values probability distributions to investigate the magnitude and frequency of extreme high flows and low flows. Yearly peak river discharges data was fitted to the Generalized Extreme Value distribution (Stedinger et al., 1993; Dung et al., 2015). Similarly, maximum cumulative discharge deficit, defined as the total deficit under a threshold, were fitted to the Generalized Pareto distribution (Tallaksen et al., 2004; Hurkmans et al., 2010) to analyse extreme low flows. The threshold to calculate cumulative discharge deficit is defined as Q75 (discharge value exceeded 75 % of the time) under future climate change (Hisdal et al., 2004). Hydrological changes were calculated under individual scenarios and under ensembles, i.e. average changes from multiple GCMs and both RCPs.

## 3 Results

### 3.1 Performance of the hydrological simulations

The calibration and validation results are presented in Table 2. The simulated river discharges in general match relatively well to the observed data. The NSE values show very good performance (0.88–0.96) for all considered stations. Similarly, the relative biases in total discharge, and the high flows (Q5) and low flows (Q95) indices are all within acceptable ranges. Model performance is weakest at the most upstream station in Chiang Saen. Discharge biases show that the hydrological model consistently underestimates discharge at Chiang Saen by 10 and 12 % of total annual flow during the calibration and validation periods, respectively. This underestimation is also shown by the flow duration curve, where simulated low flows exhibits more biases than high flows (Fig. 2). Model's lower performance could be due to inaccurate meteorological forcing data. The APHRODITE data is based on a limited number of rain gages in the mountainous area above Chiang Saen and therefore data quality might be affected. This issue, however, is only substantial at this most upstream station and validation results improve further downstream (Table 2). Lastly, daily discharge plots also show good matches between simulated and observed discharges for both calibration and validation periods (Fig. 2). Based on these validations, we conclude that the model set up is suitable for our modelling purposes.

### 3.2 Climate change projection

We analysed future changes in temperature and precipitation projected by the GCMs and RCPs by comparing climate data between the baseline (1971–2000) and future (2036–2065) periods. Since we only assessed hydrological changes down to Kratie (Cambodia), we excluded the downstream area below this station (i.e. South of latitude 12.5° N) when calculating temperature and precipitation changes.

Overall, surface air temperature is projected to increase consistently under all GCM and RCP simulations (Fig. 3). All GCMs project higher temperature increase in the RCP8.5 than in the RCP4.5. In particular, the RCP8.5 ensemble shows an increase of +2.4 °C whereas the RCP4.5 ensemble projects +1.9 °C. Temperature increase differs amongst the individual GCMs and RCPs. The lowest basin-average temperature increase of 1.5 °C is projected by the MPI-RCP4.5, whereas the ACCESS-RCP8.5 projects the highest increase of 3.5 °C. Notably, the ACCESS GCM shows markedly more temperature increase compared to other models. The spatial patterns of projected temperature increases are relatively similar between the scenarios: temperature tends to increase more in the upper catchment area in China, large parts of Thailand and sometimes also in the Vietnamese Mekong delta (Fig. 3). Areas with lower future temperature increases are located mostly in the eastern part of the Mekong's lower basin including Eastern Cambodia and the Central Highlands of Vietnam.

Total annual precipitation in the Mekong basin is projected to increase under most (i.e. 9 out of 10) climate change scenarios. Only the HadGEM-RCP8.5 scenario projects a slight reduction (i.e. −3 %) in annual precipitation. Annual precipitation changes between −3 % (HadGEM-RCP8.5) and +5 % (CCSM-RCP8.5), with an ensemble mean of +3 % across all the scenarios. The scenarios also show larger range of basin-wide precipitation changes under the RCP8.5 (i.e. between −3 and +5 %) compared to that under the RCP4.5 (i.e. between +3 and +4 %).

Despite the overall increasing signal, all scenarios project contrasting directional changes where precipitation increases in some areas and reduces in others (Fig. 4). The upper catchment area (i.e. above Chiang Saen) exhibits substantial precipitation increase under all scenarios. The lower Mekong area, on the other hand, shows both increase and reduction in annual rainfall, depending on location. Many GCMs, including CSIRO, HadGEM and MPI project rainfall reduction in the eastern part of the lower Mekong basin (i.e. Southern Laos, Eastern Cambodia and the Vietnamese central highlands). This reduction is more substantial under the RCP8.5 compared to the RCP4.5. Lastly, the spatial patterns of precipitation change show little consensus between the individual GCM's projections. The differences in precipitation change scenarios highlight a high degree of uncertainty in simulating future precipitation regimes in the Mekong basin.

## 3.3 Changes in the flow regime

This section presents changes in annual, seasonal and monthly river discharges under climate change. Annual changes are presented for all seven mainstream stations (see locations in Fig. 1) while we limit the rest of the results to three representative stations to maintain the paper's focus. These stations are Vientiane (Laos PDR), Mukdahan (Thailand) and Kratie (Cambodia), each representing the upper, middle and lower parts of the basin, respectively.

The GCM ensemble mean, lowest and highest changes in annual river discharge are presented in Table 3 for both RCPs. The ensemble means in both the RCP4.5 and the RCP8.5 show a general increase of the Mekong's mean flow under climate change. Annual discharges increase between +5 % (at Kratie and Stung Treng) and +15 % (at Chiang Saen), indicating more substantial increase in the upstream stations compared to the downstream ones. Despite the general increasing signal based on ensemble mean, annual discharges also reduce slightly under some individual scenarios.

The reductions range from −1 % (at Chiang Saen, scenario CSIR0-RCP4.5) to −7 % (at Stung Treng and Kratie, scenario HadGEM-RCP8.5). While the ensemble means under the two RCPs are very similar, the RCP8.5 exhibits a larger range in projected discharge changes (Table 3). This larger range is associated to more differentiated precipitation changes under individual GCMs in the RCP8.5 compared to those in the RCP4.5 (see Fig. 4).

Figure 5 shows changes in monthly river discharges under climate change. Overall, the scenario ensembles show higher monthly river flow at all considered stations, except for a slight reduction in June. Absolute discharge increases are more substantial in the wet season compared to those in the dry season. In terms of timing, the RCP4.5 shows largest increases in November, while the RCP8.5 shows largest increase in August. Although absolute increases are more substantial during the wet season months, relative increases are higher during the dry season. For instance, discharge in April could increase up to +40 % (+360 m$^3$ s$^{-1}$) at Vientiane and +25 % (+480 m$^3$ s$^{-1}$) at Kratie. Despite the overall increasing trends, discharge in June is projected to reduce slightly at all three stations, ranging between −810 m$^3$ s$^{-1}$ (−8 %) at Kratie, followed by −530 m$^3$ s$^{-1}$ (−8 %) at Mukdahan and −210 m$^3$ s$^{-1}$ (−5 %) at Vientiane. On the seasonal timescale, discharges increase at all stations during both the wet and dry seasons.

Cross-GCMs comparisons show that monthly discharge changes during the wet season are more variable compared to the dry season. Figure 5 clearly shows that the ensemble's projection ranges become markedly larger in the wet season, implying higher uncertainty in the hydrological change signal. For example, projected river discharge in August at Mukdahan ranges between 15 400 m$^3$ s$^{-1}$ (scenario HadGEM-RCP8.5) and 22 300 m$^3$ s$^{-1}$ (scenario MPI-RCP8.5). This is a spread of 6900 m$^3$ s$^{-1}$, equivalent to 36 % of the average discharge in August. Moreover, the individual GCMs also show contrasting directional discharge changes in the wet season months. The CSIRO and HadGEM models project reductions in discharge during June–October, whereas the other models project discharge increases during the same period. These contrasting directional changes mainly result from the disagreement among GCMs on the future precipitation regime in the Mekong basin. This disagreement highlights one of the key uncertainties in projecting future climatic change and subsequently hydrological responses in the Mekong basin, as also noted by Kingston et al. (2011).

## 3.4 Changes in hydrological extremes

This section subsequently presents changes in Q5 (high flow), Q95 (low flow) and hydrological extremes. Relative changes in high flows (Q5) and low flows (Q95) at Vientiane, Mukdahan and Kratie are shown in Fig. 6. Overall, high flows are projected to increase at all considered stations. The scenario ensemble means show increases in Q5 of +8, +5 and +6 % at Vientiane, Mukdahan and Kratie, respectively. However, high flows also slightly reduce in two scenarios. In particular, the CSIRO-RCP8.5 projects high flow reduction at Vientiane (−6 %) and Mukdahan (−3 %). Similarly, the HadGEM-RCP8.5 also suggests reductions of −1, −2 and −4 % of high flows at Vientiane, Mukdahan and Kratie, respectively. Low flows are projected to increase under all considered scenarios, implying more water availability during the dry season. On average, Q95 increases most substantially at Vientiane (+41 %), followed by Mukdahan (+30 %) and Kratie (+20 %).

The non-exceedance curves of yearly peak discharges (Fig. 7) show substantial increases in extremely high flow at all considered stations. The baseline's non-exceedance curves are always lower than those from the GCM ensemble means, implying increases in both the magnitudes and frequencies of annual peak flows. At Vientiane, for instance, the maximum river discharge occurring once every ten years is projected to increase from 23 800 to 27 900 $m^3 s^{-1}$ (RCP4.5) and 28 500 $m^3 s^{-1}$ (RCP8.5). Similarly, yearly peak discharges at Kratie increases from 61 700 to 65 000 $m^3 s^{-1}$ (RCP4.5) and 66 900 $m^3 s^{-1}$ (RCP8.5).

Lastly, both magnitude and frequency of extremely low flows are projected to reduce due to more water availability during the dry season. Higher dry season discharge results in reductions in the total discharge deficits, defined as the total deficit under a threshold (Q75 value under climate change). The non-exceedance curves in Fig. 8 shows that these deficits reduce substantially at all three representative stations. Discharge deficits are lowest at Vientiane, ranging between 68 000 $m^3 s^{-1}$ (2 year return period) and 100 000 $m^3 s^{-1}$ (20 year return period) under the baseline condition. These deficits are projected to reduce by almost 50 %, to 30 000 and 58 000 $m^3 s^{-1}$ under the RCP8.5 scenario. Similarly, discharge deficits also reduce substantially at Mukdahan and Kratie. Figure 8 also shows that future discharge deficits are relatively similar between the RCP4.5 and the RCP8.5.

## 4 Discussion

We have presented climatic and hydrological changes in the Mekong River basin based on a relatively large ensemble of CMIP5 GCMs and climate change scenarios. Motivated by improvements in CMIP5 GCMs technicalities and performance, we further analysed changes in extreme hydrological conditions under climate change. As such, our results provide important updates and new insights to the current knowledge base about hydrological response to climate change. Additionally, the results also reveal important implications for water resources management and climate change adaptation.

Our results further confirm and solidify the Mekong's hydrological intensification in response to climate change (Sect. 3.3). In general, our derived hydrological impact signals from the CMIP5 climate change scenarios are in line with findings from most previous CMIP3-based studies addressing impacts on mean discharge changes. This study projects an increase of +5 % in average annual river discharge at Kratie, compared to +10, +4 and +3 % by Hoanh et al. (2010), Västilä et al. (2010) and Lauri et al. (2012), respectively. Similar to these studies, our results also show increasing monthly and seasonal river discharges. Despite the differences in GCMs choices, climate experiment generations (i.e. CMIP5 vs. CMIP3) and downscaling approaches, the increasing trend in annual and seasonal river flow is robust across different studies. Therefore, certain confidence can be placed on the general direction of the Mekong's hydrologi-

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

cal change under climate change. Although the increasing signals derived from such scenarios ensemble are robust across studies, many studies also report discharge reductions under a few individual climate change scenarios. Also in this study, annual discharge at Kratie reduces in two scenarios (i.e. the CSIRO-RCP8.5 and HadGEM-RCP8.5). This highlights the relevance of using multiple GCMs and greenhouse gases concentration scenarios rather than relying on individual GCMs or scenarios. Such an ensemble approach allows to establish plausible ranges of future hydrological changes, given inherent differences in impact signals from individual climate experiments.

Our scenario ensembles project increases in both high flows and low flows conditions under climate change. These increases have important implications for water management in the river basin. The analyses for high flows consistently show that the Q5 and yearly peak river discharges will increase at all representative stations. Higher peak discharges occurring at higher frequencies will increase the flood risks across the basin. This can potentially have negative impacts for safety and economic development and indicates the need to take appropriate adaptation measures. The increase in discharge during the wet season will pose threats to safety of hydropower dams along the river (Cao et al., 2011; Pittock and Hartmann, 2011). The notion is particularly relevant for the Mekong, where dams are often built in cascades and such cascade dam failure could potentially cause tremendous damage for downstream areas (Cao et al., 2011). Increased wet season river discharge will also increase the flood risks in the low-lying river delta in Cambodia and Vietnam. More inflow from upstream in combination with sea level rise will further exacerbate floods and thereby causing damage for people and economic development in this most flood-prone area of the Mekong basin. On the other hand, increased water availability during the dry season suggested by the Q95 and discharge deficit analyses can have positive implications. The projected higher river discharge during the dry season months could help to mitigate water shortage in the basin. Additionally, higher dry season flow will also contribute to control salt water intrusion in the Vietnamese Mekong delta, where fresh water flow from upstream is currently used to control the salt gradient in rivers and canals in the coastal area.

We acknowledge several limitations and potential sources of error in this research. First, combining two historic climate datasets (i.e. the WATCH and the APHRODITE) may introduce errors due to inconsistencies. However, our datasets selection is motivated by careful consideration of data quality and availability. Although APHRODITE provides high quality precipitation data (Vu et al., 2012; Lauri et al., 2014), this dataset lacks temperature data needed for the hydrological model. We therefore supplement temperature data from the commonly used WATCH Forcing Data. Furthermore, the calibration and validation results show that our hydrological simulation based on the combined climate forcing data is able to realistically reproduce historic river discharge. Combinations of temperature and precipitation datasets were also shown by Lauri et al. (2014) to yield sufficient accuracy in hydrological modelling in the Mekong basin. Second, this paper only uses one bias-correction method (i.e. Piani et al., 2010) for climate data preparation. This could affect the derived hydrological impact signal (Hagemann et al., 2011) but is unlikely to change the main signal of hydrological change. Additionally, our primary interest is to understand how the Mekong's hydrology will change under climate change. Therefore, including other bias-correction methods is out if this paper's scope. Third, due to limited data availability, we could not include climate change projections from regional climate models (e.g. CORDEX) in our study. Such inclusion of highly-resolved climate projection could be a very useful addition, not only to this study, but also to the current knowledge base about the Mekong's hydrology under climate change. The scope of this study is to understand how climate change will affect Mekong's hydrology including extremes. Hydrological changes in this river basin, however, are simultaneously driven by multiple factors including irrigated land expansion, urbanization and population growth, hydropower dams and inter-basin water transfer. For example, several studies including Lauri et al. (2012), Piman et al. (2013) and MRC (2011a) have shown that irrigation expansion, hydropower dam construction and water transfer projects can largely alter flow regime. Such anthropogenic factors under the climate change context should be subjected to future studies in order to yield more integrated and comprehensive insights about the Mekong's future hydrology and water resources.

## 5 Conclusions

This study is one of the first CMIP5-based assessments on the Mekong River's hydrology under climate change. We aim to update this particularly important knowledge base, and more importantly, fill the current knowledge gap about future changes in hydrological extremes.

Climate change scenarios show that temperature consistently increases across the basin, with higher rises in the upper basin in China, large parts of Thailand and the Vietnamese Mekong delta. Basin-wide precipitation also increases under a majority of scenarios (9 out of 10), but certain areas also exhibit reducing signal. Individual GCMs and scenarios also show considerable differences in precipitation changes' patterns and magnitudes. As a result, the Mekong's hydrology will intensify, characterized by increases in annual river discharge at all stations. The scenario ensemble means also show increases in seasonal discharges, for both wet and dry seasons. Discharge increases are more substantial during the wet season, but the ensemble ranges are more variable compared to the dry season. Considerably different and sometimes contrasting directional discharge changes exist in our scenarios ensemble. This uncertainty exists in both earlier CMIP3 and CMIP5-based (this study) assessments, highlighting a key challenge in quantifying future hydrological change. It emphasizes the importance of, first, using ensemble approach in hydrological assessments, and second, developing robust, adaptive approaches to water management under climate change.

Lastly, we found substantial changes in hydrological extremes concerning both low flow and high flow conditions. Water availability during dry season consistently increases under all climate change scenarios, suggesting positive impacts on water supply and salt water intrusion control in the downstream delta. Wet season discharges and annual peak flows, on the other hand, are found to increase substantially under climate change. These increases imply important consequences for risk management, especially in checking and maintaining safety of water infrastructures, and in controlling flood risk in the downtream river delta.

## References

Adamson, P. T., Rutherfurd, I. D., Peel, M. C., Conlan, I. A., by E, and Campbell, I. C.: The Hydrology of the Mekong River, chapter 4, in: The Mekong, Academic Press, San Diego, 53–76, doi:10.1016/B978-0-12-374026-7.00004-8, 2009.

Cao, Z., Yue, Z., and Pender, G.: Flood hydraulics due to cascade landslide dam failure, J. Flood Risk Manage., 4, 104–114, doi:10.1111/j.1753-318X.2011.01098.x, 2011.

Cosslett, T. and Cosslett, P.: Major threats to Mekong Delta: climate change and mainstream dams, in: Water Resources and Food Security in the Vietnam Mekong Delta, vol 44. Natural Resource Management and Policy, Springer International Publishing, Cham Heidelberg New York Dordrecht London, 75–96, doi:10.1007/978-3-319-02198-0_3, 2014.

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, 1731–1746, doi:10.1002/hyp.6740, 2008.

Dai, A. and Trenberth, K. E.: Estimates of freshwater discharge from continents: latitudinal and seasonal variations, J. Hydrometeorol., 3, 660–687, doi:10.1175/1525-7541(2002)003<0660:eofdfc>2.0.co;2, 2002.

Delgado, J. M., Merz, B., and Apel, H.: A climate-flood link for the lower Mekong River, Hydrol. Earth Syst. Sci., 16, 1533–1541, doi:10.5194/hess-16-1533-2012, 2012.

Dung, N. V., Merz, B., Bárdossy, A., and Apel, H.: Handling uncertainty in bivariate quantile estimation–an application to flood hazard analysis in the Mekong Delta, J. Hydrol., 527, 704–717, 2015.

Eastham, J., Mpelasoka, F., Mainuddin, M., Ticehurst, C., Dyce, P., Hodgson, G., Ali, R., and Kirby, M.: Mekong River Basin Water Resources Assessment: Impacts of Climate Change, Water for a Healthy Country National Research Flagship report, CSIRO, 2008.

FAO: WRB Map of World Soil Resources, Food and Agriculture Organization of United Nations (FAO), Land and Water Development Division, Rome, 2003.

Giorgi, F. and Gutowski Jr., W. J.: Regional dynamical downscaling and the CORDEX initiative, Annu. Rev. Env. Resour., 40, 467–490, doi:10.1146/annurev-environ-102014-021217, 2015.

GLC2000: Global Land Cover 2000 Database, European Commission, Joint Research Centre, 2003.

Hagemann, S., Chen, C., Haerter, J. O., Heinke, J., Gerten, D., and Piani, C.: Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models, J. Hydrometeorol., 12, 556–578, doi:10.1175/2011JHM1336.1, 2011.

Hapuarachchi, H. A. P., Takeuchi, K., Zhou, M., Kiem, A. S., Georgievski, M., Magome, J., and Ishidaira, H.: Investigation of the Mekong River basin hydrology for 1980–2000 using the YHyM, Hydrol. Process., 22, 1246–1256, doi:10.1002/hyp.6934, 2008.

Hargraeves, G. H. and Samani, Z. A.: Estimating potential evapotranspiration, ASCE J. Irrig. Drain. Divis., 108, 225–230, 1982.

Hisdal, H., Tallaksen, L. M., Clausen, B., Peters, E., and Gustard, A.: Hydrological drought characteristics, in: Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater, Elsevier, Amsterdam, Boston, Heidelberg, London, New York, Paris, S an Diego, San Francisco, Singapore, Sydney, Tokyo, 139–198, 2004.

Hoanh, C. T., Jirayoot, K., Lacombe, G., and Srinetr, V.: Impacts of climate change and development on Mekong flow regime, First assessment – 2009, MRC technical paper no. 29, Mekong River Commission, Vientiane, Lao PDR, 2010.

Huang, Y., Wang, F., Li, Y., and Cai, T.: Multi-model ensemble simulation and projection in the climate change in the Mekong River Basin. Part I: Temperature, Environ. Monit. Assess., 186, 7513–7523, doi:10.1007/s10661-014-3944-x, 2014.

Hurkmans, R., Terink, W., Uijlenhoet, R., Torfs, P., Jacob, D., and Troch, P. A.: Changes in streamflow dynamics in the Rhine basin under three high-resolution regional climate scenarios, J. Climate, 23, 679–699, 2010.

Jacobs, J. W.: The Mekong River Commission: transboundary water resources planning and regional security, Geogr. J., 168, 354–364, doi:10.1111/j.0016-7398.2002.00061.x, 2002.

Jarvis, A., Reuter, H., Nelson, A., and Guevara, E.: Hole-filled SRTM for the globe Version 4, CGIAR-CSI SRTM 90 m Database, CGIAR, available at: http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1, 2008.

Junk, W., Brown, M., Campbell, I., Finlayson, M., Gopal, B., Ramberg, L., and Warner, B.: The comparative biodiversity of seven globally important wetlands: a synthesis, Aquat. Sci., 68, 400–414, doi:10.1007/s00027-006-0856-z, 2006.

Keskinen, M., Chinvanno, S., Kummu, M., Nuorteva, P., Snidvongs, A., Varis, O., and Västilä, K.: Climate change and water resources in the Lower Mekong River Basin: putting adaptation into the context, J. Water Clim. Change, 1, 103–117, doi:10.2166/wcc.2010.009, 2010.

Kingston, D. G., Thompson, J. R., and Kite, G.: Uncertainty in climate change projections of discharge for the Mekong River Basin, Hydrol. Earth Syst. Sci., 15, 1459–1471, doi:10.5194/hess-15-1459-2011, 2011.

Knutti, R. and Sedlacek, J.: Robustness and uncertainties in the new CMIP5 climate model projections, Nature Climate Change, 3, 369–373, 2013.

Krysanova, V., Wortmann, M., Bolch, T., Merz, B., Duethmann, D., Walter, J., Huang, S., Tong, J., Buda, S., and Kundzewicz, Z. W.: Analysis of current trends in climate parameters, river discharge and glaciers in the Aksu River basin (Central Asia), Hydrolog. Sci. J., 60, 566–590, doi:10.1080/02626667.2014.925559, 2014.

Lamberts, D. and Koponen, J.: Flood pulse alterations and productivity of the Tonle Sap ecosystem: a model for impact assessment, Ambio, 37, 178–184, 2008.

Lauri, H., Veijalainen, N., Kummu, M, Koponen, J., Virtanen, M., Inkala, A., and Sark, J.: VMod Hydrological Model Manual, Finnish Environment Institute, EIA Ltd., Helsinki University of Technology, Helsinki, 2006.

Lauri, H., de Moel, H., Ward, P. J., Räsänen, T. A., Keskinen, M., and Kummu, M.: Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge, Hydrol. Earth Syst. Sci., 16, 4603–4619, doi:10.5194/hess-16-4603-2012, 2012.

Lauri, H., Räsänen, T. A., and Kummu, M.: Using reanalysis and remotely sensed temperature and precipitation data for hydrological modeling in monsoon climate: Mekong River case study, J. Hydrometeorol., 15, 1532–1545, doi:10.1175/jhm-d-13-084.1, 2014.

Lebel, L., Garden, P., and Imamura, M.: The politics of scale, position, and place in the governance of water resources in the Mekong Region, Ecol. Soc., 10, available at: http://www.ecologyandsociety.org/vol10/iss2/art18/, 2005.

Leng, G., Tang, Q., and Rayburg, S.: Climate change impacts on meteorological, agricultural and hydrological droughts in China, Global Planet. Change, 126, 23–34, doi:10.1016/j.gloplacha.2015.01.003, 2015.

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, doi:10.1002/joc.1181, 2005.

MRC: Overview of the Hydrology of the Mekong Basin, Tech. rep, Mekong River Commission, Vientiane, Laos PDR, 2005.

MRC: The Flow of the Mekong, Mekong River Commission, Vientiane, Laos PDR, 2009.

MRC: State of the Basin Report 2010, Mekong River Commission, Vientiane, Lao PDR, 2010.

MRC: Assessment of Basin-wide Development Scenarios: Main Report – Basin Development Plan Programme, Mekong River Commission, Vientiane, Lao PDR, 2011a.

MRC: Hydrometeorological database of the Mekong River Commission, Mekong River Commission, Vientiane, Lao PDR, 2011b.

Nakicenovic, N., Alcamo, J., Davis, G., De Vries, H. J. M., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., La Rovere, E. L., Michaelis, L., Mori, S., Morita, T., Papper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H- H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., Van Rooijen, S., Victor, N., and Dadi, Z.: Emissions Scenarios, a Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2000.

Nash, J. and Sutcliffe, J. V.: River flow forecasting through conceptual models. Part I – A discussion of principles, J. Hydrol., 10, 282–290, 1970.

Pech, S. and Sunada, K.: Population growth and natural-resources pressures in the Mekong River Basin, Ambio, 37, 219–224, doi:10.1579/0044-7447(2008)37[219:pganpi]2.0.co;2, 2008.

Piani, C., Weedon, G. P., Best, M., Gomes, S. M., Viterbo, P., Hagemann, S., and Haerter, J. O.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models, J. Hydrol., 395, 199–215, doi:10.1016/j.jhydrol.2010.10.024, 2010.

Piman, T., Lennaerts, T., and Southalack, P.: Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios, Hydrol. Process., 27, 2115–2125, doi:10.1002/Hyp.9764, 2013.

Pittock, J. and Hartmann, J.: Taking a second look: climate change, periodic relicensing and improved management of dams, Mar. Freshwater Res., 62, 312–313, 2011.

Renaud, F. G., Kuenzer, C., Delgado, J., Merz, B., and Apel, H.: Monsoon variability and the Mekong flood regime, in: The Mekong Delta System, Springer Environmental Science and Engineering, Springer Netherlands, Dordrecht Heidelberg New York London, 233–244, doi:10.1007/978-94-007-3962-8_9, 2012.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rafaj, P.: RCP 8.5 – a scenario of comparatively high greenhouse gas emissions, Climatic Change, 109, 33–57, doi:10.1007/s10584-011-0149-y, 2011.

Sarkkula, J., Koponen, J., Lauri, H., and Virtanen, M.: IWRM Modelling Report, Detailed Modelling Support (DMS), Information and Knowledge Management Programme, Mekong River Commission, Vientiane, Laos PDR, 2010.

Shabehul, H., Salvatore, P., Valerio, L., and Jürgen, B.: Seasonal cycle of precipitation over major river basins in south and southeast Asia: a review of the CMIP5 climate models data for present climate and future climate projections, Atmos. Res., under review, 2015.

Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W., and Bronaugh, D.: Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate, J. Geophys. Res.-Atmos., 118, 1716–1733, doi:10.1002/jgrd.50203, 2013.

Smajgl, A., Toan, T. Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., Tri, V. P. D., and Vu, P. T.: Responding to rising sea levels in the Mekong Delta, Nature Climate Change, 5, 167–174, 2015.

Stedinger, J. R., Vogel, R. M., and Foufoula-Georgiou, E.: Frequency analysis of extreme events, in: Handbook of Hydrology, edited by: Maidment, D. R., McGraw-Hill, New York, 18.11–18.66, 1993.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (eds.): Climate Change 2013: the Physical Science Basis, contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

Tallaksen, L. M. and van Lanen, H. A. J. (eds.): Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater, Developments in Water Science, vol. 48, Elsevier, Amsterdam, Boston, Heidelberg, London, New York, Paris, San Diego, San Francisco, Singapore, Sydney, Tokyo, 579 pp., 2004.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, doi:10.1175/bams-d-11-00094.1, 2011.

Thomson, A., Calvin, K., Smith, S., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M., Clarke, L., and Edmonds, J.: RCP4.5: a pathway for stabilization of radiative forcing by 2100, Climatic Change, 109, 77–94, doi:10.1007/s10584-011-0151-4, 2011.

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Berg, L. V. D., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J. F., Morcrette, J. J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Q. J. Roy. Meteor. Soc., 131, 2961–3012, doi:10.1256/qj.04.176, 2005.

van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P., and Kabat, P.: Global river discharge and water temperature under climate change, Global Environ. Chang., 23, 450–464, doi:10.1016/j.gloenvcha.2012.11.002, 2013.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., and Lamarque, J.-F.: The representative concentration pathways: an overview, Climatic Change, 109, 5–31, 2011.

Varis, O., Kummu, M., and Salmivaara, A.: Ten major rivers in monsoon Asia-Pacific: an assessment of vulnerability, Appl. Geogr., 32, 441–454, doi:10.1016/j.apgeog.2011.05.003, 2012.

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

Veldkamp, T. I. E., Wada, Y., de Moel, H., Kummu, M., Eisner, S., Aerts, J. C. J. H., and Ward, P. J.: Changing mechanism of global water scarcity events: impacts of socioeconomic changes and inter-annual hydro-climatic variability, Global Environ. Chang., 32, 18–29, doi:10.1016/j.gloenvcha.2015.02.011, 2015.

Vogel, R. M. and Fennessey, N. M.: Flow duration curves. II. A review of applications in water resource planning, Water Resour. Bull., 31, 1029–1039, 1995.

Vu, M. T., Raghavan, S. V., and Liong, S. Y.: SWAT use of gridded observations for simulating runoff – a Vietnam river basin study, Hydrol. Earth Syst. Sci., 16, 2801–2811, doi:10.5194/hess-16-2801-2012, 2012.

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N., Boucher, O., and Best, M.,: Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century, J. Hydrometeorol., 12, 823–848, doi:10.1175/2011jhm1369.1, 2011.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A.: APHRODITE: constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, B. Am. Meteorol. Soc., 93, 1401–1415, doi:10.1175/bams-d-11-00122.1, 2012.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., and Levin, S. A.: Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin, P. Natl. Acad. Sci. USA, 109, 5609–5614, doi:10.1073/pnas.1201423109, 2012.

**Table 1.** Selected CMIP5 GCMs for climatic and hydrological change assessment.

| GCM name | Acronyms | Institution | Resolution (lon × lat) |
|---|---|---|---|
| ACCESS1-0 | ACCESS | CSIRO-BOM – Commonwealth Scientific and Industrial Research Organisation, Australia and Bureau of Meteorology, Australia | $1.875^{\circ} \times 1.25^{\circ}$ |
| CCSM4 | CCSM | NCAR – National Center for Atmospheric Research | $1.25^{\circ} \times 0.94^{\circ}$ |
| CSIRO-Mk3.6.0 | CSIRO | CSIRO-QCCCE – Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence | $1.875^{\circ} \times 1.875^{\circ}$ |
| HadGEM2-ES | HadGEM | MOHC – Met Office Hadley Centre and Instituto Nacional de Pesquisas Espaciais | $1.875^{\circ} \times 1.24^{\circ}$ |
| MPI-ESM-LR | MPI | MPI-M Max Planck Institute for Meteorology | $1.875^{\circ} \times 1.875^{\circ}$ |

**Table 2.** Model performance indices calculated from daily time series for calibration (C) and validation (V) periods. See station locations in Fig. 1.

| Stations | NSE | | Relative total bias | | Q5 high flow relative bias | | Q95 low flow relative bias | |
|---|---|---|---|---|---|---|---|---|
| | C | V | C | V | C | V | C | V |
| Chiang Saen | 0.90 | 0.90 | 0.90 | 0.88 | 0.93 | 0.91 | 0.64 | 0.62 |
| Vientiane | 0.92 | 0.88 | 1.08 | 1.10 | 1.12 | 1.14 | 0.85 | 0.81 |
| Nakhon Phanom | 0.96 | 0.96 | 1.03 | 1.03 | 1 | 0.85 | 0.92 | 0.72 |
| Mukdahan | 0.96 | 0.95 | 0.98 | 1 | 0.96 | 0.89 | 0.81 | 0.7 |
| Pakse | 0.94 | 0.94 | 0.94 | 0.91 | 0.88 | 0.88 | 0.89 | 0.82 |
| StungTreng | 0.94 | 0.97 | 0.93 | 0.89 | 0.86 | 0.84 | 1.09 | 0.86 |
| Kratie | 0.95 | 0.93 | 1.00 | 0.90 | 0.91 | 0.85 | 1.01 | 0.83 |

**Table 3.** Relative changes in annual river discharges at the Mekong's mainstream stations for 2036–2065 relative to 1971–2000. Lowest and highest changes are presented with the corresponding climate change scenarios.

| Station | RCP 4.5 | | RCP 8.5 | |
|---|---|---|---|---|
| | Ensemble mean (%) | Range (%) | Ensemble mean (%) | Range (%) |
| Chiang Saen | +14 | +4 – +29<br>CSIRO – ACCESS | +15 | −1 – +33<br>CSIRO – ACCESS |
| Vientiane | +9 | +1 – +17<br>CSIRO – ACCESS | +9 | −1 – +20<br>CSIRO – ACCESS |
| Nakhon Phanom | +7 | −1 – +12<br>CSIRO – ACCESS | +6 | −2 – +13<br>CSIRO – ACCESS |
| Mukdahan | +6 | −1 – +11<br>CSIRO – ACCESS | +5 | −4 – +13<br>HadGEM – ACCESS |
| Pakse | +6 | +2 – +10<br>CCSM – ACCESS | +5 | −6 – +13<br>HadGEM – MPI |
| Stung Treng | +5 | +3 – +8<br>CCSM – ACCESS | +5 | −7 – +10<br>HadGEM – ACCESS |
| Kratie | +5 | +3 – +8<br>CCSM – ACCESS | +5 | −7 – +11<br>HadGEM – MPI |

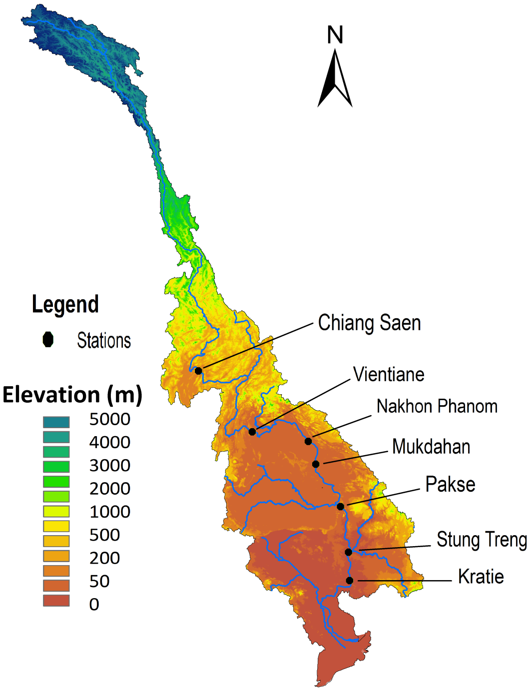

**Figure 1.** The Mekong River basin's elevation map and locations of mainstream gauging stations.

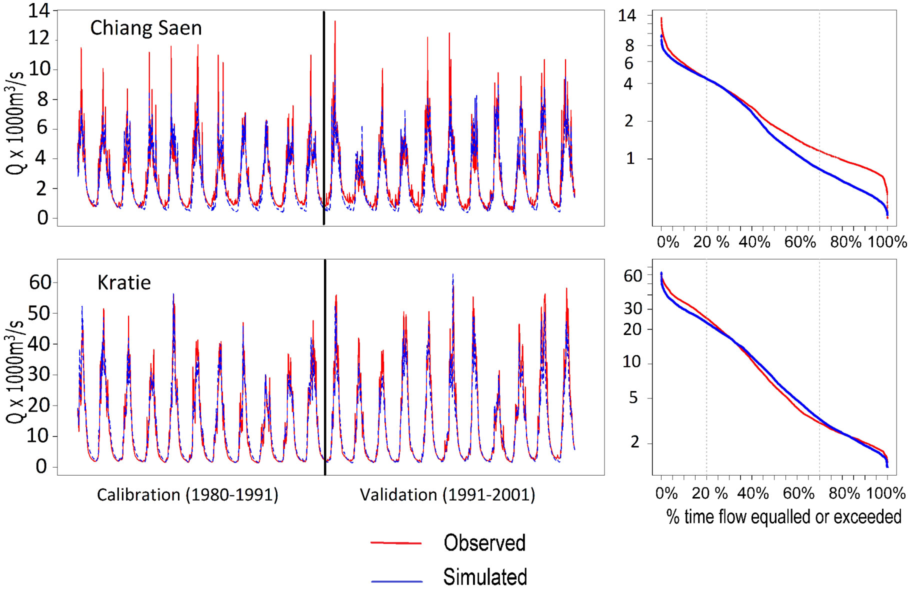

**Figure 2.** Daily discharge plots (left) and flow duration curves (right) during calibration and validation at Chiang Saen (upper plots) and Kratie (lower plots). See station locations in Fig. 1.

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

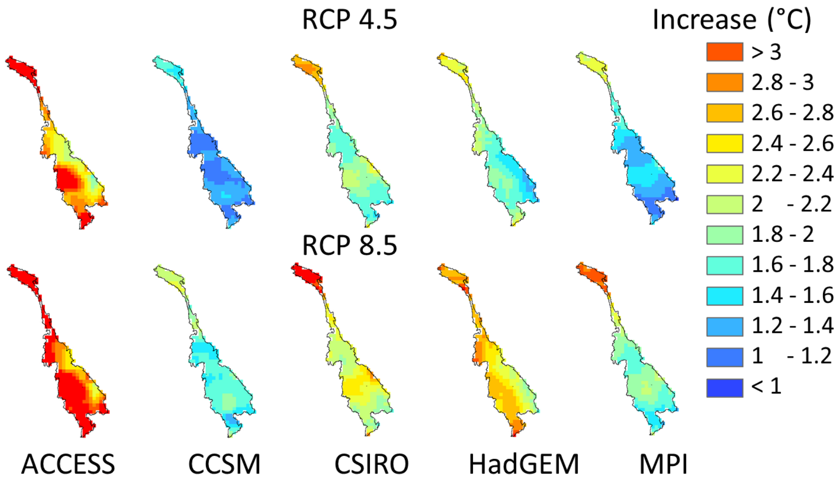

**Figure 3.** Projected change in daily mean temperature (°C) under future climate (2036–2065) compared to baseline situation (1971–2000).

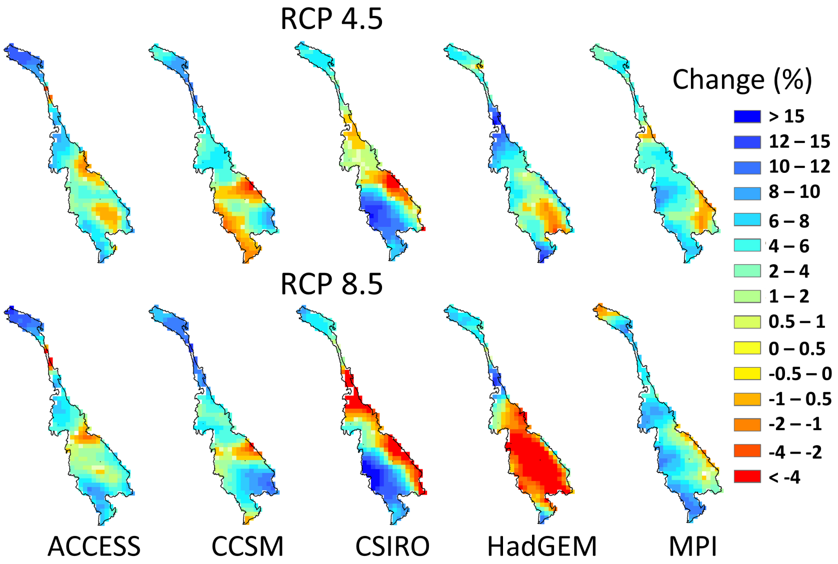

**Figure 4.** Projected change in total annual precipitation (%) under future climate (2036–2065) compared to the baseline climate (1971–2000).

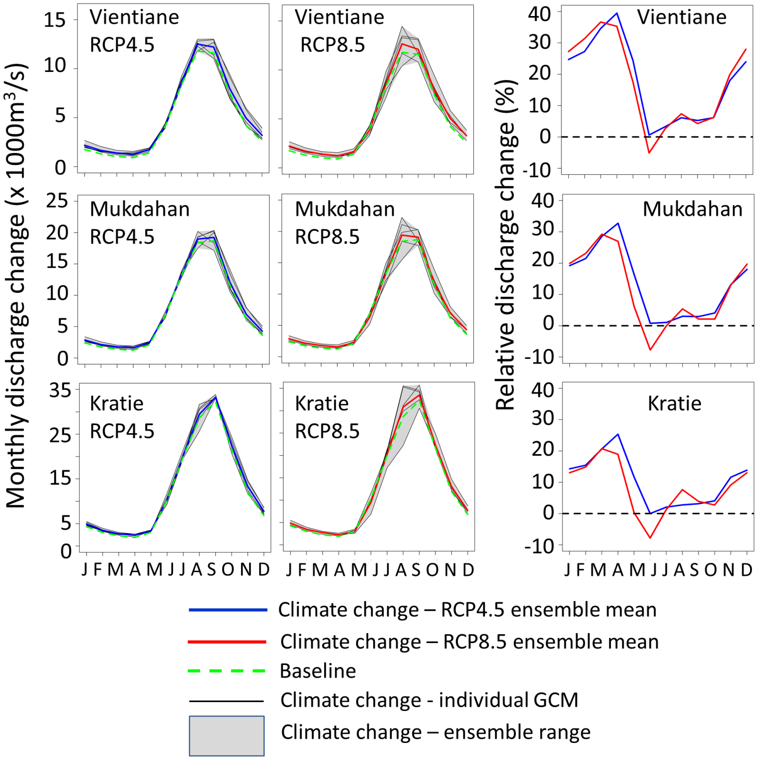

**Figure 5.** Projected monthly river discharge (left and middle panels) and relative changes (right panel) under climate change for 2036–2065 relative to 1971–2000.

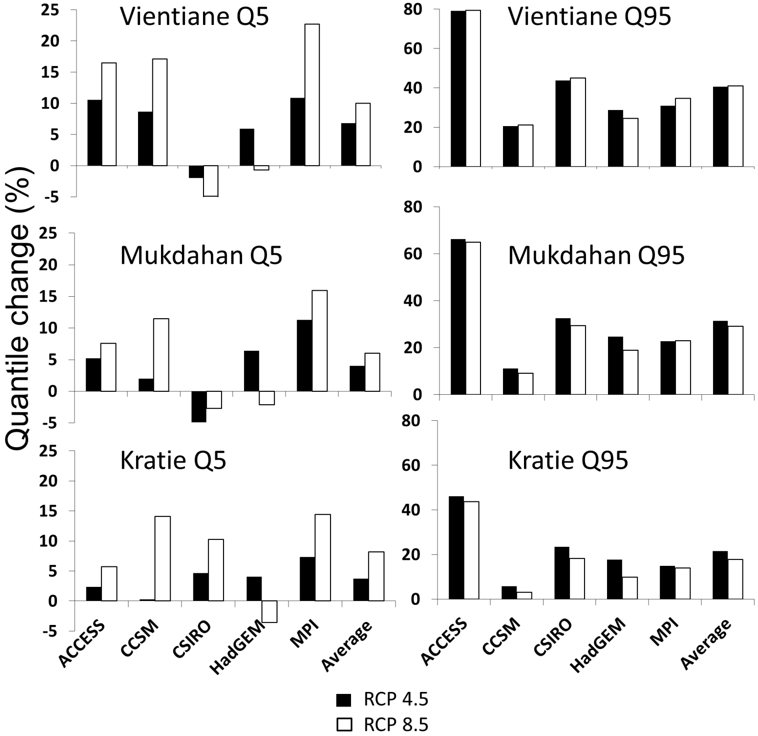

**Figure 6.** Projected changes in Q5 (high flow) and Q95 (low flow) under climate change for 2036–2065 relative to 1971–2000.

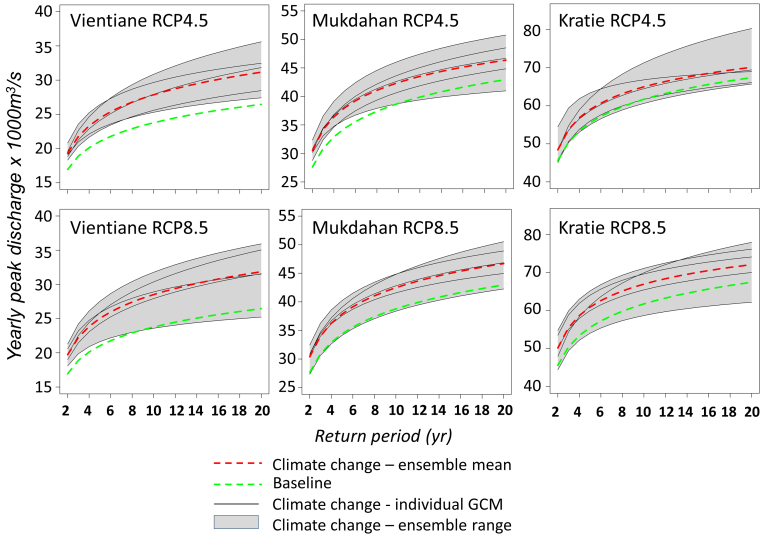

**Figure 7.** Non-exceedance curves of yearly peak discharges under baseline (1971–2000) and future climate (2036–2065).

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

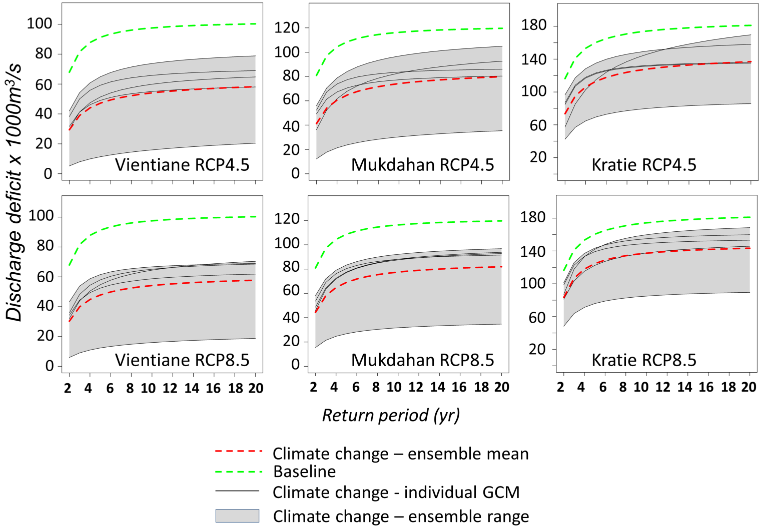

**Figure 8.** Non-exceedance curves of yearly maximum cumulative discharge deficits (i.e. total deficit below the Q75 threshold) under baseline and future climate.

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