Mekong River flow and hydrological extremes under climate change

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Abstract

Climate change poses critical threats to water related safety and sustainability in the Mekong River basin. Hydrological impact signals from earlier CMIP3-based assessments, however, are highly uncertain and largely ignore hydrological extremes. This paper provides one of the first hydrological impact assessments using the CMIP5 climate projections. Furthermore, we model and analyse changes in river flow regimes and hydrological extremes (i.e. high flow and low flow conditions). In general, the Mekong's hydrological cycle intensifies under future climate change. 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. The scenarios ensemble, however, shows reduced uncertainties in climate projection and hydrological impacts compared to earlier CMIP3-based assessments. 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. Climate change induced hydrological changes will have important implications for safety, economic development and ecosystem dynamics and thus require special attention in climate change adaptation and water management.

Keywords: Climate change, river flow, hydrological extremes, CMIP5, Mekong

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 across six different countries, namely China, Myanmar, Laos PDR, Thailand, Cambodia and finally Vietnam before draining into the East Sea (also known as 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). 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). Given high dependencies on water in the basin, the issues of securing water safety and long-term sustainability are especially important for water resources management.

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 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 the 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 due to 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 many 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 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 scenarios in projecting monthly discharge changes and 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 associates with uncertainties in the climate change projection, especially precipitation changes. Given these uncertainties, 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. Compared to uncertainty in the future climate, uncertainty relating to hydrological models' schematization and parameterization seems less important for the Mekong basin. Regarding hydrological model's skill, many studies including Hoanh et al., 2010; Västilä et al., 2010; Kingston et al. (2011) and Lauri et al. (2012) reported sufficient performance in capturing the dynamics of the Mekong's hydrology. Several studies also reported lower modelling skill in more upstream stations (e.g. Chiang Saen) compared to more downstream stations including Kingston et al. (2011) and Lauri et al. (2012).

Notably, all earlier studies used the SRES emission scenarios (Nakicenovic et al., 2000), which were developed for the Climate Models Inter-comparison Project phase 3 (CMIP3). These 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. the CMIP5) are not yet routinely used to assess the hydrological impacts in the Mekong basin. The CMIP5 scenarios also exhibit important improvements, both in terms of the GCMs' technical development (Taylor et al., 2011; Knutti and Sedláček, 2013) and the efficiency to reproduce the historic climate conditions (Shabeh uh 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 hydrological signal will be reduced as well.

Second, although hydrological extremes under future climatic change are very 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 to 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 (Sect. 3.1 and 4.1). We selected a set of 10 climate change experiments for five GCMs and two RCPs from the CMIP5 and performed a downscaling and bias-correction on the climate model output (Sect. 3.2). Future changes in precipitation and temperature (Sect. 4.2) and subsequently the Mekong's annual and monthly discharge changes were quantified (Sect. 4.3). In addition, we quantified changes in hydrological extremes, focusing on both extreme low and high flows (Sect. 4.4). We will also reflect on the robustness of the hydrological signals and show improvements in uncertainty compared to other CMIP3-based studies (Sect. 5.1).

2 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 795,000km^2, distributed unevenly across six Southeast Asian countries (MRC, 2005). The river's annual discharge volume of 475km^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 per unit area, owing to its dominant tropical monsoon climate (Adamson et al., 2009; Renaud et al., 2012). Elevation in the basin ranges between above 5,000m in the Tibetan Plateau to only a few meters above sea level in the downstream river delta.

[Figure 1]

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-West 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 delta (i.e. the Tonle Sap Lake in Cambodia and the Vietnamese Mekong delta), supports a highly productive aquatic ecosystem and one of the world's major rice production area (Lamberts and Koponen, 2008; Arias et al., 2012).

Hydrological changes, including changes in extreme high and low flows, increase safety risks and undermine economic productivity in the basin, especially in the low-lying river delta (Eastham et al., 2008; Arias et al., 2014). 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 (Cosslett and Cosslett, 2014) illustrates the 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 upstream inflow 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).

3 Methodology

3.1 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 soil surface processes are simulated following Dingman (1994). After calculating the water balance, runoff 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 5km x 5km 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 5km x 5km grid. 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 GLC2000 provides land cover data that is most suitable to our calibration and validation time period (i.e., 1981-2001). The flow direction data was prepared from the SRTM90m 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 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). Simulation performance was further improved by manually 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).

3.2 Climate data

We prepared climate data for the historic period (1971-2000) and the future period (2036-2065) using various datasets. Historic temperature 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; 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 gauges 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). We further discuss potential implications of using the combined WATCH-APHRODITE data in Sect.5.3.

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, implying their suitability to be used in the Mekong region. 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. Shabeh uh 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 4.5W/m^2 by 2100 (Thomson et al., 2011). The RCP8.5 is a high radiative forcing scenario assuming a rising radiative forcing leading to 8.5W/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. Given our focus on hydrological extremes under climate change, we did not consider RCP2.6, which is the lowest radiative forcing scenario.

[Table 1]

Since the GCMs' spatial resolution is generally too coarse for a basin-scale study, we re-gridded the climate data to a 0.5°x0.5° 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).

3.3 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 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.

4 Results

4.1 Performance of the hydrological simulations

[Table 2]

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, except for relatively lower performance at the most upstream Chiang Saen station. Discharge biases show underestimation of annual discharge at Chiang Saen by 10% and 12% during the calibration and validation, respectively. This underestimation is also shown by the flow duration curve, where simulated low flows exhibits more biases than high flows (Fig. 2). Low flow biases at Chiang Saen could be explained by unaccounted flow regulation by upstream hydropower dams during the dry season, as suggested by Adamson (2001), Lauri et al. (2012) and Räsänen et al. (2012). Besides, lower accuracy of APHRODITE precipitation data in the mountainous area above Chiang Saen could also affect the model's performance. Discharge biases, however, are only substantial at Chiang Saen station and quickly improve further downstream (see 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.

[Figure 2]

4.2 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 increases consistently under all GCMs and RCPs (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. A majority of scenarios project temperature increases between 1.5°C and 2.5°C, including CCSM-RCP8.5, CSIRO-RCP4.5, CSIRO-RCP8.5, HadGEM-RCP4.5, HadGEM-RCP8.5 and MPI-RCP4.5. Notably, the ACCESS GCM shows markedly more temperature increase compared to other models. The spatial patterns of 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.

[Figure 3]

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%). Notably, these ranges of precipitation changes are typically smaller than those derived from earlier CMIP3-based assessments (i.e. Eastham et al., (2008); Kingston et al., (2011); Lauri et al., (2012) and Thompson et al., (2013)). Details on cross-studies comparison are shown in Table 4. Reduced uncertainties in precipitation projection will likely improve robustness of the projected hydrological changes.

[Figure 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), especially under the RCP8.5 scenario.

4.3 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).

[Table 3]

Fig. 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% (+360m^3/s) at Vientiane and +25% (+480m^3/s) at Kratie. Despite the overall increasing trends, discharge in June is projected to reduce slightly at all three stations, ranging between -810m^3/s (-8%) at Kratie, followed by -530m^3/s (-8%) at Mukdahan and -210m^3/s (-5%) at Vientiane. On the seasonal timescale, discharges increase at all stations during both the wet and dry seasons.

[Figure 5]

Cross-GCMs comparisons show that monthly discharge changes during the wet season are more variable compared to the dry season. Fig. 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 15,400m^3/s (scenario HadGEM-RCP8.5) and 22,300m^3/s (scenario MPI-RCP8.5). This is a spread of 6,900m^3/s, 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).

4.4 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%).

[Figure 6]

[Figure 7]

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 23,800m^3/s to 27,900m^3/s (RCP4.5) and 28,500m^3/s (RCP8.5). Similarly, yearly peak discharges at Kratie increases from 61,700m^3/s to 65,000m^3/s (RCP4.5) and 66,900m^3/s (RCP8.5).

[Figure 8]

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 68,000m^3/s (2-yr return period) and 100,000m^3/s (20-yr return period) under the baseline condition. These deficits are projected to reduce by almost 50%, to 30,000m^3/s and 58,000m^3/s under the RCP8.5 scenario. Similarly, discharge deficits also reduce substantially at Mukdahan and Kratie. Fig. 8 also shows that future discharge deficits are relatively similar between the RCP4.5 and the RCP8.5.

5 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.

5.1 Comparison: Impact signal and improvements in uncertainties

Our results further confirm and solidify the Mekong's hydrological intensification in response to climate change (Sect. 4.3, 4.4). In general, hydrological impact signals from the CMIP5 scenarios are in line with findings from most previous CMIP3-based studies. 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 versus 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 hydrological change under climate change.

[Table 4]

Furthermore, the projected impact signals in this study exhibit less uncertainty compared to similar CMIP3-based assessments. A cross-study comparison (see Table 4) for the representative Kratie station shows that both the impact signal's range and cross-scenarios agreement on directional changes improved markedly in this CMIP5-based study. In particular, the ranges of annual discharge change, i.e. 3% to 8% (RCP4.5) and -7% to 11% (RCP8.5) are typically smaller than those projected by earlier studies including Eastham et al. (2008), Kingston et al. (2011), Lauri et al., (2012) and Thompson et al., (2013). Similarly, the projected precipitation changes also show less uncertainty in the CMIP5 scenarios compared to the CMIP3 scenarios. Additionally, directional discharge changes also shows better consensus in this study. The CMIP5-based ensemble's impact signal (i.e. increasing annual discharge) is supported by nine out of ten individual scenarios, whereas other studies show relatively lower consensus. Lastly, we compared uncertainty in hydrological extremes by calculating the coefficient of variation for projected yearly peak discharges between studies. Due to limited data availability, we only compared our study with Lauri et al. (2012). Both studies have ensembles of ten projections, grouped into a mid-range scenario (i.e. RCP4.5 versus SRES-B1) and a high scenario (i.e. RCP8.5 versus SRES-A1B). Overall, our CMIP5-based projection exhibits lower uncertainty, shown by lower coefficients of variation for both the mid-range scenarios (24% versus 38%) and the high scenario (25% versus 38%). Reduced uncertainty detected in our study is also in line with studies by Sperber et al., (2012) and

Shabeh Uh et al. (2015) where they found improved representations of the Asian summer monsoon by the CMIP5 models.

5.2 Implications for water management

Projected hydrological changes, especially increases in high flows and low flows conditions under climate change show important implications for water management in the river basin. Firstly, higher peak discharges occurring at higher frequencies during the wet season will increase the flood risks across the basin. Higher flood risk will be particularly relevant for human safety and agricultural production in the lower Mekong region, including the Cambodian and Vietnamese delta. Vast agriculture areas along the main rivers and in the delta's floodplain will likely experience higher flood water levels, thus having higher risks of reduced productivity and crop failure. Higher river flow, combined with sea level rise will also result in higher flood risks for urban areas in the Mekong Delta.

Secondly, 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. 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. Additionally, projected discharge reduction at the beginning of the wet season (i.e. in June) probably has negative impacts on ecological and agricultural productivity. Flow alteration in the early wet season will likely change the sediment and nutrient dynamics in the downstream floodplains, which are very important for existing ecosystems and agricultural practices (Arias et al., 2012). Lastly, rainfall reduction in some areas of the lower Mekong could damage agricultural production, especially rainfed agriculture.

5.3 Limitations and way forward

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, calibration and validation results show that our hydrological simulation based on the combined climate forcing data is able to realistically reproduce historic river discharge. Given relatively lower modelling skill at Chiang Saen, interpreting hydrological impact signal at this station requires extra caution. 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, including other bias-correction methods is outside this paper's scope given our primary interest to understand how the Mekong's hydrology will change under climate change. 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 useful, not only for this study, but also for 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, however, are simultaneously driven by multiple factors including irrigated land expansion, urbanization, 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 should be subjected to future studies in order to yield more comprehensive insights about the Mekong's future hydrology and water resources. Of special importance in this regard is the need to assess the interactions between different drivers and the resulted hydrological changes.

6 Conclusions

This study is one of the first hydrological impact assessments for the Mekong River basin focusing on hydrological extremes under climate change. We aim to cover this particularly important knowledge gap, and thereby better informing and supporting policy and decision making in the Southeast Asia's largest river basin.

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. 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, although reduces markedly compared to earlier CMIP3-based assessments, highlights a 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 salinity control in the downstream delta. Wet season discharges and annual peak flows will increase substantially, implying important consequences for risk management, especially in securing safety of water infrastructures, and in controlling flood risk in the Mekong delta. Given robust evidences of changes in hydrological extremes, shifting research and management focuses to these low-probability but potentially high-damage events is important to reduce climate change impacts and associated risks.

References

Adamson, P.T. 2001. Hydrological perspectives on the Lower Mekong Basin: The potential impacts of hydropower developments in Yunnan on the downstream flow regime. Int. Water Power Dam Constr. March 2001, 16–21

Adamson, P.T., Rutherfurd, I.D., Peel, M.C., Conlan, I.A., by E, Campbell I.C. (2009) Chapter 4 - The Hydrology of the Mekong River. In: The Mekong. Academic Press, San Diego, pp 53-76. doi:http://dx.doi.org/10.1016/B978-0-12-374026-7.00004-8

Arias, M.E., Cochrane, T.A., Piman, T., Kummu, M., Caruso, B.S. and Killeen, T.J., (2012) Quantifying changes in flooding and habitats in the Tonle Sap Lake (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin. Journal of environmental management, 112, pp.53-66

Arias, M.E., Cochrane, T.A., Kummu, M., Lauri, H., Holtgrieve, G.W., Koponen, J. and Piman, T. (2014) Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. Ecological modelling, 272, pp.252-263

Cosslett, T., Cosslett, P. (2014) 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, pp 75-96. doi:10.1007/978-3-319-02198-0_3

Costa-Cabral, M.C., Richey, J.E., Goteti, G., Lettenmaier, D.P., Feldkötter, C., Snidvongs, A. (2008) Landscape structure and use, climate, and water movement in the Mekong River basin. Hydrol Process 22 (12):1731-1746. doi:10.1002/hyp.6740

Dai, A., Trenberth, K.E. (2002) Estimates of Freshwater Discharge from Continents: Latitudinal and Seasonal Variations. Journal of Hydrometeorology 3 (6):660-687. doi:10.1175/1525-7541(2002)003<0660:eofdfc>2.0.co;2

Dingman, S.L., (1994) Water in soils: infiltration and redistribution. Physical hydrology (Vol. 575). Englewood Cliffs, NJ: Prentice Hall

Delgado, J.M., Merz, B., Apel, H. (2012) A climate-flood link for the lower Mekong River. Hydrol Earth Syst Sci 16 (5):1533-1541. doi:10.5194/hess-16-1533-2012

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

Eastham, J., Mpelasoka, F., Mainuddin, M., Ticehurst, C., Dyce, P., Hodgson, G., Ali, R., Kirby, M. (2008) Mekong River Basin water resources assessment: Impacts of climate change, Water for a Healthy Country National Research Flagship report. CSIRO.

FAO (2003) WRB map of world soil resources. Food and Agriculture Organization of United Nations (FAO), Land and Water Development Division

Giorgi, F. & W.J. Gutowski Jr, Regional Dynamical Downscaling and the CORDEX Initiative, Annual Review of Environment and Resources, DOI: 10.1146/annurev-environ-102014-021217

GLC2000 (2003) Global Land Cover 2000 database. European Commission, Joint Research Centre,

Hagemann, S., Chen, C., Haerter, J.O., Heinke, J., Gerten, D., and Piani, C., 2011: Impact of a Statistical Bias Correction on the Projected Hydrological Changes Obtained from Three GCMs and Two Hydrology Models. J. Hydrometeor, 12, 556–578. doi: http://dx.doi.org/10.1175/2011JHM1336.1

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

Hisdal, H., Tallaksen, L. M., Clausen, B., Peters, E., Gustard, A. (2004) Hydrological drought characteristics. Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater, Elsevier, 139–198.

Hoanh, C.T., Jirayoot, K., Lacombe, G., Srinetr, V. (2010) Impacts of climate change and development on Mekong flow regime, First assessment – 2009. MRC Technical Paper No. 29. Mekong River Commission, Vientiane, Lao PDR

Huang, Y., Wang, F., Li, Y., Cai, T. (2014) Multi-model ensemble simulation and projection in the climate change in the Mekong River Basin. Part I: temperature. Environmental Monitoring and Assessment 186 (11):7513-7523. doi:10.1007/s10661-014-3944-x

Hurkmans, R., Terink, W., Uijlenhoet, R., Torfs, P., Jacob, D., & Troch, P. A. (2010) Changes in streamflow dynamics in the Rhine basin under three high-resolution regional climate scenarios. Journal of Climate, 23(3), 679-699.

Jacobs, J.W. (2002) The Mekong River Commission: transboundary water resources planning and regional security. Geographical Journal 168 (4):354-364. doi:10.1111/j.0016-7398.2002.00061.x

Jarvis, A., Reuter, H., Nelson, A., Guevara, E. (2008) Hole-filled SRTM for the globe Version 4, CGIAR-CSI SRTM 90m Database.

Keskinen, M., Chinvanno, S., Kummu ,M., Nuorteva, P., Snidvongs, A., Varis, O., Västilä, K. (2010) Climate change and water resources in the Lower Mekong River Basin: putting adaptation into the context. J Water Clim Change 1 (2):103–117. doi:10.2166/wcc.2010.009

Kingston, D.G., Thompson, J.R., Kite, G. (2011) Uncertainty in climate change projections of discharge for the Mekong River Basin. Hydrol Earth Syst Sci 15 (5):1459-1471. doi:10.5194/hess-15-1459-2011

Knutti, R., Sedlacek, J. (2013) Robustness and uncertainties in the new CMIP5 climate model projections. Nature climate change 3 (4):369-373

Lamberts, D., Koponen, J. (2008) Flood pulse alterations and productivity of the Tonle Sap ecosystem: a model for impact assessment. Ambio 37 (3):178-184

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

Lauri, H., Moel, H. D., Ward, P. J., Räsänen, T. A., Keskinen, M., & Kummu, M. (2012). Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge. Hydrology and Earth System Sciences, 16(12), 4603-4619.

Lauri, H., Räsänen, T.A., Kummu, M. (2014) Using Reanalysis and Remotely Sensed Temperature and Precipitation Data for Hydrological Modeling in Monsoon Climate: Mekong River Case Study. Journal of Hydrometeorology 15 (4):1532-1545. doi:10.1175/jhm-d-13-084.1

Lebel, L., Garden, P., Imamura, M. (2005) The Politics of Scale, Position, and Place in the Governance of Water Resources in the Mekong Region. Ecology and Society 10 (2)

Leng, G., Tang, Q., Rayburg, S. (2015) Climate change impacts on meteorological, agricultural and hydrological droughts in China. Global and Planetary Change 126:23-34. doi:http://dx.doi.org/10.1016/j.gloplacha.2015.01.003

Mitchell, T.D., Jones, P.D. (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25 (6):693-712. doi:10.1002/joc.1181

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

MRC (2009) The flow of the Mekong. Mekong River Commission, Vientiane, Laos PDR

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

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

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

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., Dadi, Z. (2000) Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge, Cambridge University Press.

Nash, J., Sutcliffe, J.V. (1970) River flow forecasting through conceptual models part I—A discussion of principles. J Hydrol 10 (3):282-290

Piani, C., Weedon, G.P., Best, M., Gomes, S.M., Viterbo, P., Hagemann, S., Haerter, J.O. (2010) Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. J Hydrol 395 (3–4):199-215. doi:http://dx.doi.org/10.1016/j.jhydrol.2010.10.024

Piman, T., Lennaerts, T., Southalack, P. (2013) Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios. Hydrol Process 27 (15):2115-2125. doi:Doi 10.1002/Hyp.9764

Räsänen, T.A., Koponen, J., Lauri, H. and Kummu, M., (2012). Downstream hydrological impacts of hydropower development in the Upper Mekong Basin. Water Resources Management, 26(12), pp.3495-3513

Renaud, F.G., Kuenzer, C., Delgado, J., Merz, B., Apel, H. (2012) Monsoon Variability and the Mekong Flood Regime. In: The Mekong Delta System. Springer Environmental Science and Engineering. Springer Netherlands, pp 233-244. doi:10.1007/978-94-007-3962-8_9

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P. (2011) RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Climatic Change 109 (1-2):33-57. doi:10.1007/s10584-011-0149-y

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

Shabeh ul, H., Salvatore, P., Valerio, L., Jürgen, B. (2015) 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. Atmospheric Research (Under review)

Sillmann, J., Kharin, V.V., Zhang, X., Zwiers, F.W., Bronaugh, D. (2013) Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. J Geophys Res Atmos 118 (4):1716-1733. doi:10.1002/jgrd.50203

Smajgl, A., Toan, T.Q., Nhan, D.K., Ward, J., Trung, N.H., Tri, L.Q., Tri, V.P.D., Vu, P.T. (2015) Responding to rising sea levels in the Mekong Delta. Nature climate change 5 (2):167-174

Sperber, K.R., Annamalai, H., Kang, I.S., Kitoh, A., Moise, A., Turner, A., Wang, B. and Zhou, T., (2013) The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Climate Dynamics, 41(9-10), pp.2711-2744

Stedinger, J.R., Vogel, R.M., Foufoula-Georgiou, E., 1993. Frequency analysis of extreme events. In: Maidment, D.R. (Ed.), Handbook of hydrology, McGraw-Hill, New York, pp. 18.11–18.66

Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, editors. (2013) 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, United Kingdom and New York, NY, USA.

Tallaksen, L. M., and H. A. J. van Lanen, Eds., (2004) Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, Vol. 48, Elsevier, 579 pp.

Taylor, K.E., Stouffer, R.J., Meehl, G.A. (2011) An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society 93 (4):485-498. doi:10.1175/bams-d-11-00094.1

Thomson, A., Calvin, K., Smith, S., Kyle, G.P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M., Clarke, L., Edmonds, J. (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change 109 (1-2):77-94. doi:10.1007/s10584-011-0151-4

Thompson, J.R., Green, A.J., Kingston, D.G. and Gosling, S.N., 2013. Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. Journal of hydrology, 486, pp.1-30

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., Woollen, J. (2005) The ERA-40 re-analysis. QJR Meteorol Soc 131 (612):2961-3012. doi:10.1256/qj.04.176

van Vliet, M.T.H., Franssen,W.H.P., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., Kabat, P. (2013) Global river discharge and water temperature under climate change. Global Environmental Change 23 (2):450-464. doi:http://dx.doi.org/10.1016/j.gloenvcha.2012.11.002

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

Varis, O., Kummu, M., Salmivaara, A. (2012) Ten major rivers in monsoon Asia-Pacific: An assessment of vulnerability. Applied Geography 32 (2):441-454. doi:http://dx.doi.org/10.1016/j.apgeog.2011.05.003

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

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

Vogel, R.M. and Fennessey, N.M., (1995) Flow duration curves. II. A review of applications in water resource planning. Water Resources Bulletin, 31(6): 1029-1039

Vu, M. T., Raghavan, S. V., Liong, S. Y., (2012) 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

Weedon, G.P., Gomes, S., Viterbo, P., Shuttleworth, W.J., Blyth, E., Österle, H., Adam, J.C., Bellouin, N., Boucher, O., Best, M., (2011). Creation of the WATCH Forcing Data and Its Use to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth Century. Journal of Hydrometeorology 12 (5):823-848. doi:10.1175/2011jhm1369.1

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., Kitoh, A. (2012) APHRODITE: Constructing a Long-Term Daily Gridded Precipitation Dataset for Asia Based on a Dense Network of Rain Gauges. Bulletin of the American Meteorological Society 93 (9):1401-1415. doi:10.1175/bams-d-11-00122.1

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

GCM name	Acronyms	Institution	Resolution (lon x lat)
ACCESS1-0	ACCESS	CSIRO-BOM - Commonwealth Scientific and Industrial Research Organisation, Australia and Bureau of Meteorology, Australia	1.875° x 1.25°
CCSM4	CCSM	NCAR - National Center for Atmospheric Research	1.25° x 0.94°
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° x 1.875°
HadGEM2-ES	HadGEM	MOHC - Met Office Hadley Centre and Instituto Nacional de Pesquisas Espaciais	1.875° x1.24°
MPI-ESM-LR	MPI	MPI-M Max Planck Institute for Meteorology	1.875° x1.875°

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 CSIRO - ACCESS	+15	-1 - +33 CSIRO - ACCESS
Vientiane	+9	+1 - +17 CSIRO - ACCESS	+9	-1 - +20 CSIRO - ACCESS
Nakhon Phanom	+7	-1 - +12 CSIRO - ACCESS	+6	-2 - +13 CSIRO – ACCESS
Mukdahan	+6	-1 - +11 CSIRO - ACCESS	+5	-4 - +13 HadGEM - ACCESS
Pakse	+6	+2 - +10 CCSM - ACCESS	+5	-6 - +13 HadGEM - MPI
Stung Treng	+5	+3 - +8 CCSM - ACCESS	+5	-7 - +10 HadGEM - ACCESS
Kratie	+5	+3 - +8 CCSM - ACCESS	+5	-7 - +11 HadGEM - MPI

Table 4. Comparing projected precipitation and discharge changes across studies.

	Eastham et al. 2008	Kingston et al. 2011	Lauri et al. 2012	Thompson et al. 2013	**Hoang et al. 2015 (this study)**
Range of annual precipitation change	0.5% to 36% (A1B)	-3% to 10% (up to 6°C warming)	-2.5% to 8.6% (A1B) 1.2% to 5.8% (B1)	-3% to 12.2% (2°C warming)	**3% to 4% (RCP4.5)** **-3% to 5% (RCP8.5)**
Scenarios projecting higher annual precipitation	Not available	4 out of 7	9 out of 10	4 out of 7	**9 out of 10**
Range of annual discharge change	Not available	-5.4% to 4.5% (up to 6°C warming)	-10.6% to 13.4% (A1B) -6.9% to 8.1 % (B1)	-14.7% to +8.2% (2°C warming)	**3% to 8% (RCP4.5)** **-7% to 11% (RCP8.5)**
Scenarios projecting higher annual discharge	Majority of GCMs show increasing trend	4 out of 7	7 out of 10	3 out of 7	**9 out of 10**

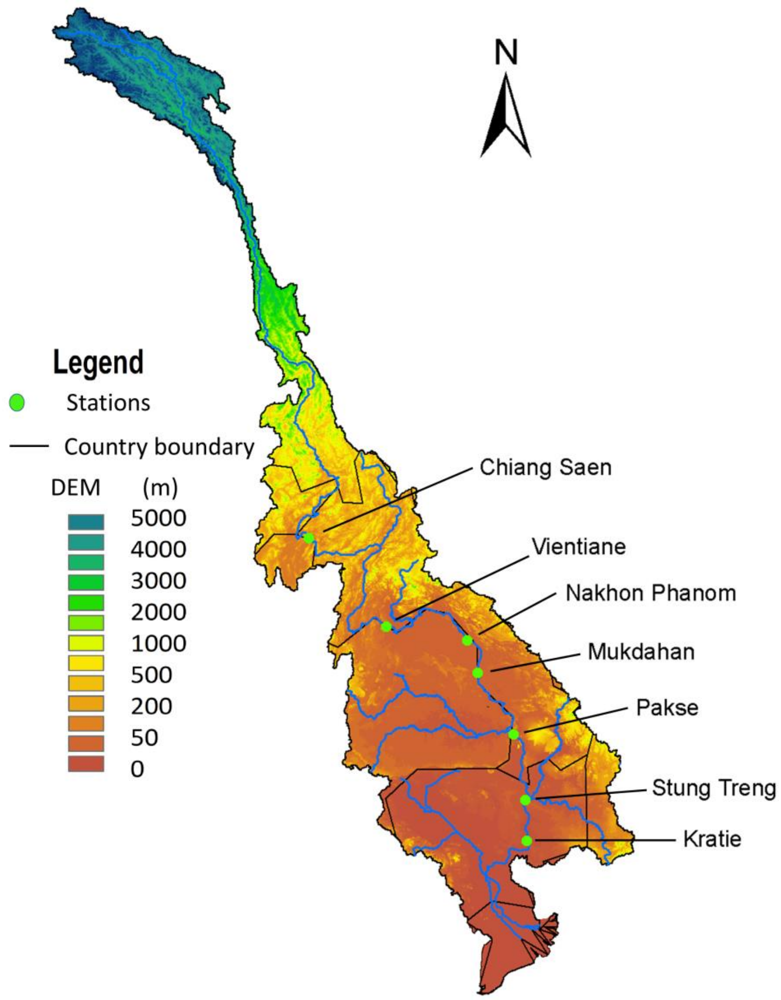

Figure 1. The Mekong River basin's elevation map and locations of mainstream gauging stations.

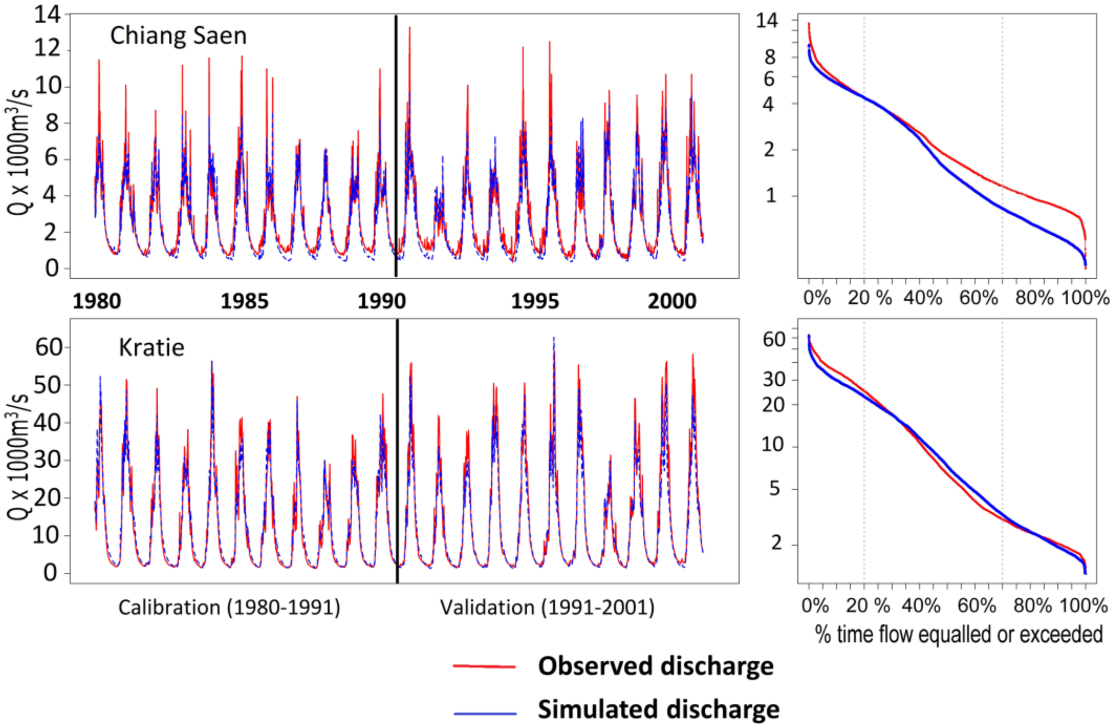

Figure 2. Daily discharge plots (left) and flow duration curves (right) during calibration and validation at Chiang Saen (upper plots) and Kratie (lower plots). See station locations in Fig. 1

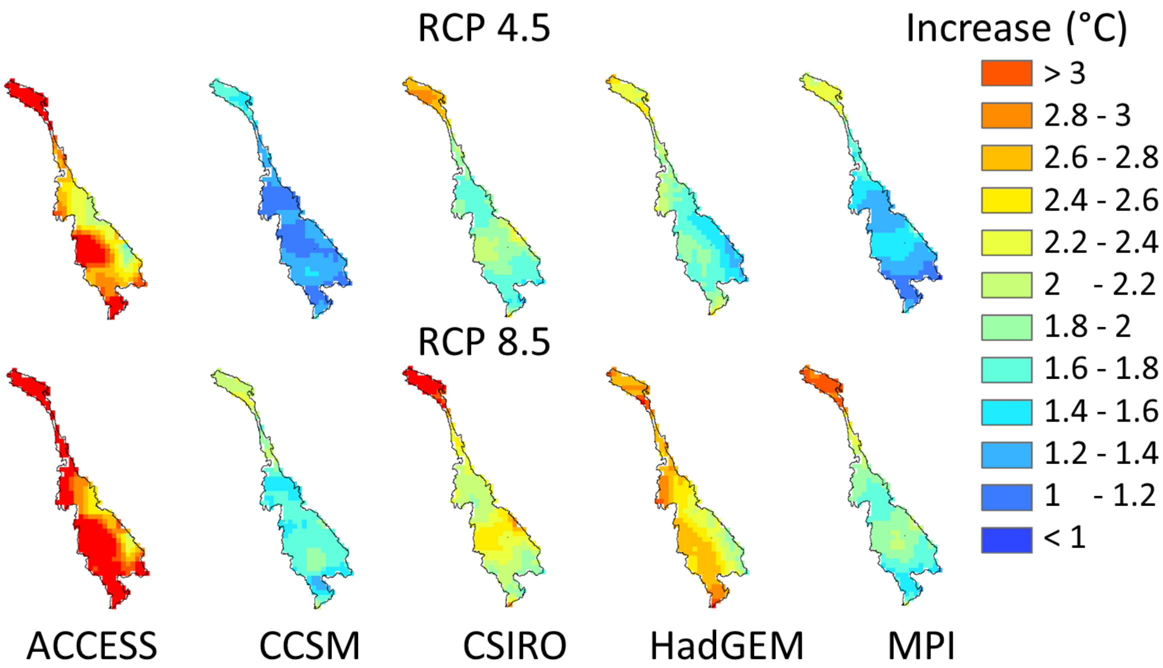

Figure 3. Projected change in daily mean temperature (°C) under future climate (2036-2065) compared to baseline situation (1971-2000).

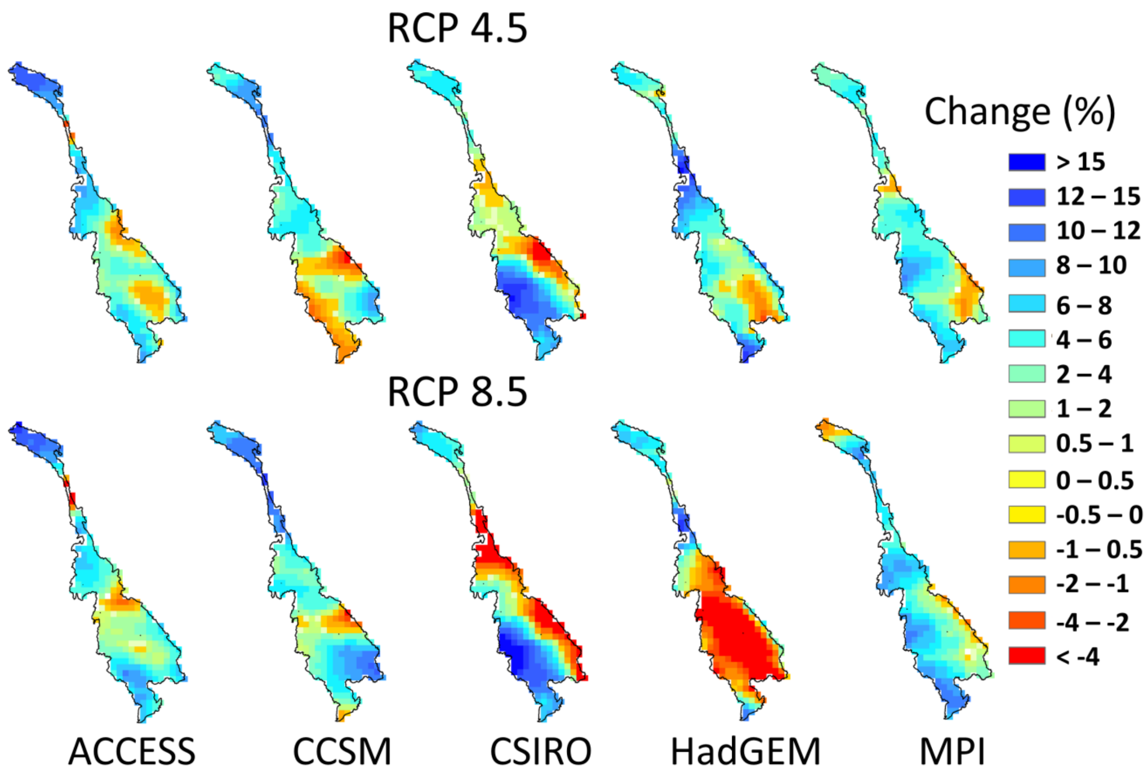

Figure 4. Projected change in total annual precipitation (%) under future climate (2036-2065) compared to the baseline climate (1971-2000).

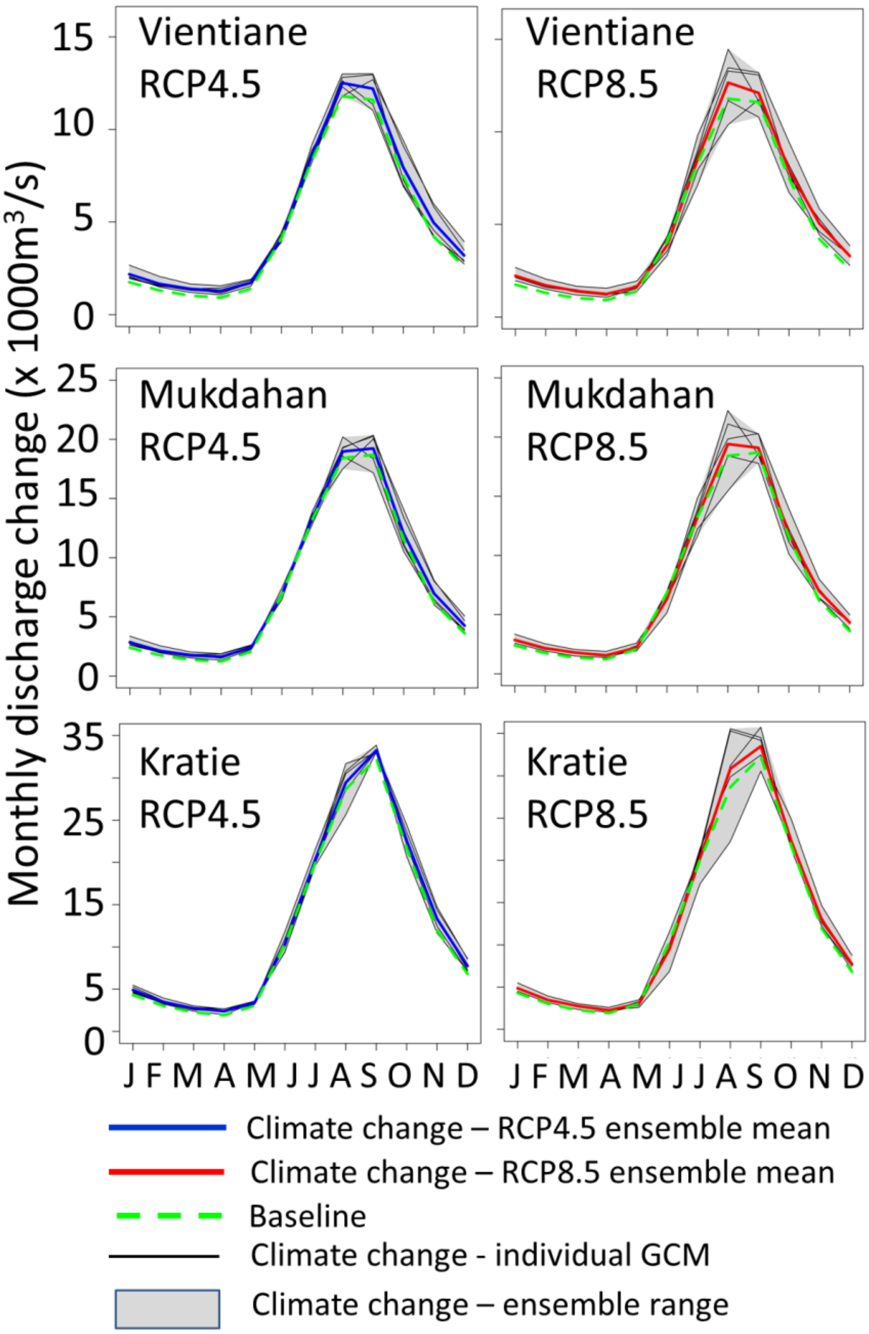

Figure 5. Projected monthly river discharge (left and middle panels) and relative changes (right panel) under climate change for 2036-2065 relative to 1971-2000.

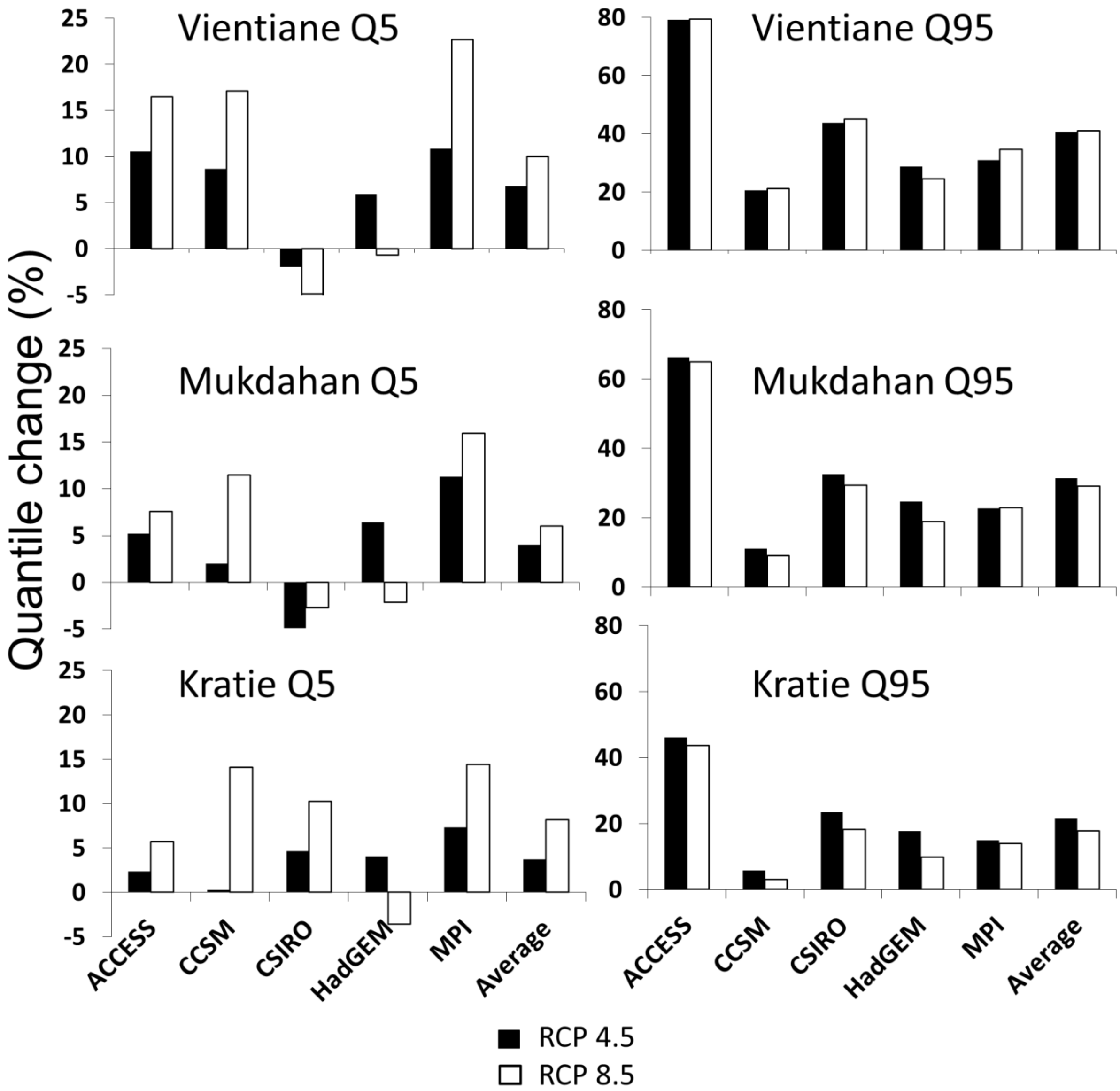

Figure 6. Projected changes in Q5 (high flow) and Q95 (low flow) under climate change for 2036-2065 relative to 1971-2000.

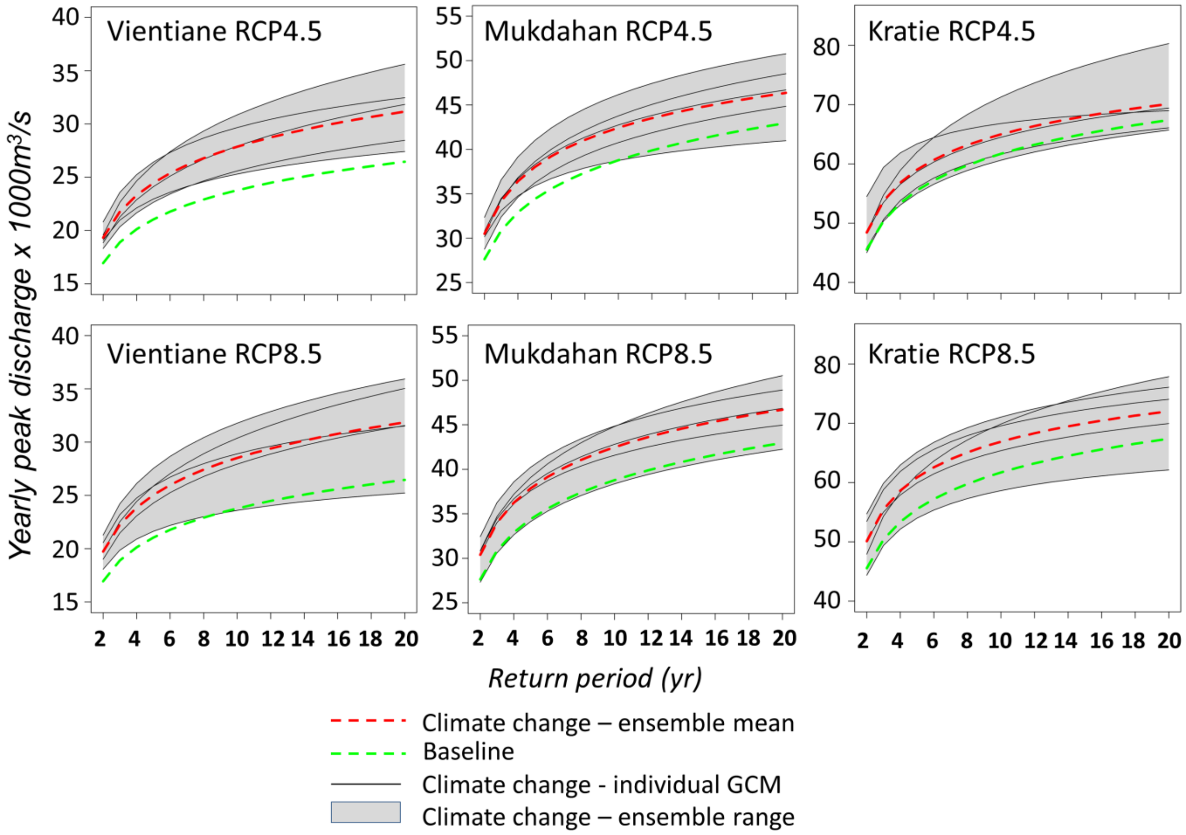

Figure 7. Non-exceedance curves of yearly peak discharges under baseline (1971-2000) and future climate (2036-2065).

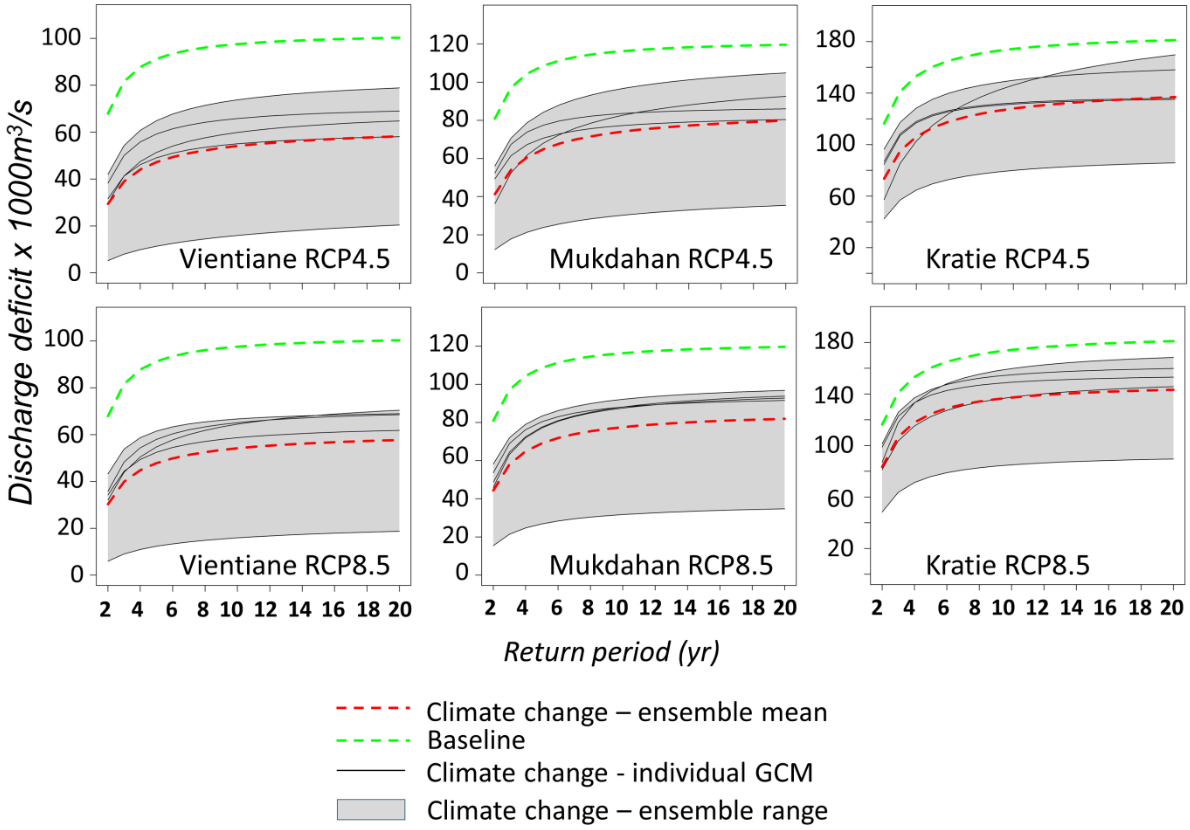

Figure 8. Non-exceedance curves of yearly maximum cumulative discharge deficits (i.e. total deficit below the Q75 threshold) under baseline and future climate