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Potential evapotranspiration-related uncertainty in climate change impacts on river flow: An assessment for the Mekong River basin

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SUMMARY

Six MIKE SHE models of the Mekong are developed, each employing potential evapotranspiration (PET) derived using alternative methods: Blaney–Criddle (BC), Hamon (HM), Hargreaves–Samani (HS), Linacre (LN), Penman (PN) and Priestley–Taylor (PT). Baseline (1961–1990) PET varies, with PT followed by HS providing the lowest totals, LN and BC the highest. The largest mean annual PET is over 1.5 times the smallest. Independent calibration of each model results in different optimised parameter sets that mitigate differences in baseline PET. Performance of each model is "excellent" (monthly NSE > 0.85) or "very good" (NSE: 0.65–0.85). Scenarios based on seven GCMs for a 2 °C increase in global mean temperature are investigated. Inter-GCM variation in precipitation change is much larger (in percentage terms by 2.5–10 times) than inter-GCM differences in PET change. Precipitation changes include catchment-wide increases or decreases as well as spatially variable directions of change, whereas PET increases for all scenarios. BC and HS produce the smallest changes, LN and HM the largest. PET method does impact scenario discharges. However, GCM-related uncertainty for change in mean discharge is on average 3.5 times greater than PET method-related uncertainty. Scenarios with catchment-wide precipitation increases (decreases) induce increases (decreases) in mean discharge irrespective of PET method. Magnitude of change in discharge is conditioned by PET method; larger increases or smaller declines in discharge result from methods producing the smallest PET increases. Uncertainty in the direction of change in mean discharge due to PET method occurs for scenarios with spatially variable precipitation change, although this is limited to few gauging stations and differences are relatively small. For all scenarios, PET method-related uncertainty in direction of change in high and low flows occurs, but seasonal distribution of discharge is largely unaffected. As such, whilst PET method does influence projections of discharge, variation in the precipitation climate change signal between GCMs is a much larger source of uncertainty.

1. Introduction

The projected impacts of climate change on the global hydrological cycle will have potentially significant implications for water resources (Bates et al., 2008; Gosling et al., 2011b; Gosling, 2012) and aquatic ecosystems (Poff et al., 2002; Matthews and Quesne, 2009). Hydrological impacts of climate change are commonly assessed by forcing a hydrological model with climate projections derived from General Circulation Models (GCMs) that are, in turn, forced with emissions scenarios. This approach has been used for global-scale assessments (Arnell, 2003; Nohara et al., 2006; Gosling et al., 2010; Arnell and Gosling, 2013), at regional (Arnell, 1999a) and national scales (Andréasson et al., 2004), and for individual catchments ranging in size from major river basins (Conway and Hulme, 1996; Nijssen et al., 2001) to medium and small sized catchments (Chun et al., 2009; Thompson et al., 2009, Thompson, 2012).

Uncertainty is associated with each stage of climate change hydrological impact assessments (Nawaz and Adeloye, 2006; Gosling et al., 2011a). There is uncertainty connected to the definition of greenhouse gas emissions scenarios with which GCMs are forced. Climate model structural uncertainty, which results from the different approaches used to represent the climate system within different GCMs, may lead to variable climate projections for the same emissions scenario. Downscaling of GCM projections to finer spatial and temporal scales for hydrological modelling is another source of uncertainty (e.g. Prudhomme and Davies, 2009).

A final source of uncertainty that in comparison to GCM-related uncertainty has received relatively little attention (Prudhomme

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and Davies, 2009) is related to the hydrological models that translate climate scenarios to hydrological impacts (Gosling et al., 2011a). Research suggests, however, that this source of uncertainty may not be negligible (e.g. Dibike and Coulibaly, 2005; Haddeland et al., 2011; Hagemann et al., 2012; Thompson et al., 2013a). Hydrological models range from global models (e.g. Döll et al., 2003; Gosling and Arnell, 2011), through lumped or semi-distributed catchment models (e.g. Arnold et al., 1998), to fully distributed, physically based models (e.g. Refsgaard et al., 2010).

Hydrological model-related uncertainty may become evident when different hydrological models are applied to the same catchment. Although the models may produce equally acceptable results for an observed baseline period, they may subsequently respond differently when forced with the same GCM projections (Haddeland et al., 2011). For example, Gosling et al. (2011a) demonstrated differences in simulated discharge for the same set of climate change scenarios from catchment models and a global hydrological model for six river basins around the world, with changes in mean runoff varying by up to 25%. Thompson et al. (2013a) extended this analysis for the Mekong by developing a second catchment hydrological model (using MIKE SHE) and comparing results with the earlier catchment model (SLURP; Kingston et al., 2011) and the Mac-PDM.09 global model. Although in most cases the direction of change in mean discharge was the same for the different models for the same climate scenario, the magnitude of change varied. In particular, the global model projected increases in discharge at some upstream gauging stations that were three to five times as large as those for the catchment models. A possible explanation for these differences is the different potential evapotranspiration (PET) methods employed by the three models.

Previous research has demonstrated that different PET methods can produce very different climate change signals, with implications for assessments of the impacts of climate change on water resources (e.g. Arnell, 1999b; Kay and Davies, 2008; Bae et al., 2011). Kingston et al. (2009) demonstrated different PET climate change signals on a global basis using six alternative PET methods. PET-related uncertainty was of a similar magnitude or, in some cases, greater than GCM-related uncertainty for individual methods. Using a simple latitudinally averaged aridity index, it was shown that different PET methods could influence the projected direction of change in global water availability. Gosling and Arnell (2011) demonstrated large differences in runoff when two alternative PET methods, Penman–Monteith and Priestley–Taylor, were used within Mac-PDM.09. These differences varied depending on location; higher runoff was generated using the second PET method in relatively dry regions, whilst negative anomalies resulted for wetter regions. Bae et al. (2011) used three alternative semi-distributed catchment models and different PET methods to simulate climate change scenarios for a medium sized catchment (c. 7000 km^2) in central South Korea. Results showed that the different PET methods impacted runoff changes, with the magnitude of PET-related differences varying between hydrological models and season.

The PET method(s) employed within a hydrological model may, therefore, be a specific source of hydrological model-related uncertainty but one that has been relatively under-investigated (Prudhomme and Williamson, 2013). There are over 50 different PET methods that could be employed within hydrological models (Lu et al., 2005). PET method selection may be influenced by a number of factors. Where a hydrological model calculates PET internally, the method will depend upon those incorporated within the model (Bae et al., 2011). Data availability may also exert an important influence since different PET methods require different meteorological variables. This may have important implications for climate change assessments since less confidence is placed in GCM simulations of some variables such as cloud cover and vapour pressure compared to others, most notably temperature (Randall et al., 2007). Similarly, other variables, such as wind speed and net radiation, are typically less reliable in the gridded datasets often used for baseline simulations (e.g. Haddeland et al., 2011) due to measurement difficulties and the relatively limited number of observations (New et al., 1999). Although many large-scale (global) hydrological models use either the Penman–Monteith or Priestley–Taylor methods, these decisions are often based on the theoretically more realistic nature of these methods as opposed to a large-scale validation of their output (although Sperna Weiland et al. (2012) is an exception).

The current study investigates the implications of using alternative PET methods for discharge projections for the Mekong River of southeast Asia. This is achieved using the MIKE SHE model developed by Thompson et al. (2013a) and its recalibration for five additional PET methods. Subsequently each of these models are used to simulate climate change scenarios based on projections from seven GCMs for a 2 °C increase in global mean temperature.

2. Methods

2.1. The Mekong catchment

The Mekong is the largest river in southeast Asia. It is the world's eighth largest in terms of annual discharge (475 km^3), 12th longest (c. 4350 km) and 21st largest by drainage area (795,000 km^2) (Kiem et al., 2008). Rising in the Tibetan Highlands at an elevation of over 5100 m, it passes through six countries before discharging into the South China Sea via the distributaries of the Mekong Delta (Fig. 1).

The dominant climatic influence is the Asian monsoon. Rains begin in mid-May and extend into early-October, with over 90% of annual precipitation falling within this period (Kite, 2001). Annual precipitation ranges from under 1000 mm on the Korat Plateau of eastern Thailand to over 3200 mm in mountainous parts of Laos. Snow is restricted to parts of the Tibetan Highlands and Yunan and covers approximately 5% of the catchment between November and March. Snowmelt contributes to the initial rise of the annual flood within the upper catchment (the Lancang; Kiem et al., 2005). River discharge begins to rise in May and peaks between August and October. The subsequent recession continues until March–April.

The upper catchment is characterised by narrow, steep gorges. Land cover is primarily tundra and montane semi-desert (Kite, 2001). Further downstream, natural vegetation is dominated by evergreen and deciduous forest (Ishidaira et al., 2008). Rapid economic development, growing populations and conflicts have, however, caused widespread deforestation in favour of agriculture (Nobuhiro et al., 2008; Lacombe et al., 2010). Additional pressures stem from competition for water, contamination by agriculture, industry and settlements, and unsustainable use of resources such as fisheries. Dams have been implicated in changes in discharge, sediment flows and fisheries (Hapuarachchi et al., 2008; Li and He, 2008; Kummu et al., 2010; Wang et al., 2011). Future dams will exacerbate these changes (Stone, 2010).

2.2. The MIKE SHE model of the Mekong

MIKE SHE is a modelling system that simulates the major processes of the land phase of the hydrological cycle (Graham and Butts, 2005). It has been employed in small catchments (Al Khudhairy et al., 1999; Thompson et al., 2004; Thompson, 2012), catchments of hundreds or thousands of km^2 (Feyen et al., 2000; Huang et al., 2010; Singh et al., 2010, 2011) and major international river basins (Andersen et al., 2001; Stisen et al., 2008). Although often