Snow cover and precipitation impacts on dry season streamflow in the Lower Mekong Basin

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1. Introduction

Water resources supplied by the Mekong River support agriculture, fisheries, ecosystems, and economic activity throughout the river basin [Adamson et al., 2009; Adamson and Bird, 2010]. Streamflow (discharge) in the Mekong River is highly seasonal and tuned to the timing of the Asian summer monsoon, with highest annual discharge occurring in late summer and early fall (September–October) and lowest discharge at the tail end of the dry season (March–May). The wet season flood pulse is controlled by summer monsoon precipitation and input from left-bank tributaries in Lao PDR and Vietnam, while dry season streamflow depends primarily on local precipitation and snowmelt contributions from the upper-basin in the Yunnan region of China [Adamson, 2006; Adamson et al., 2009; Kingston et al., 2011; Kiem et al., 2005]. Streamflow during the dry season is especially important for ecosystems and populations in the region, helping maintain local navigation and water quality, providing water for irrigation, and minimizing saltwater intrusion into the delta in Vietnam [Adamson et al., 2009; Adamson and Bird, 2010; Haddeland et al., 2006; Prathumratana et al., 2008].

In this study, we analyze the hydrologic controls (precipitation and snow cover) on discharge during the tail end of the dry, low flow season (March–April–May, MAM) in the Lower Mekong Basin (LMB). We focus on two gauging stations bounding the LMB along the main stem of the Mekong River: Vientiane (18°N–103°E) in northern Lao PDR and Kratie (13°N–106°E) in Cambodia. Our objectives are to (1) quantify the impact of Asian snow cover and regional precipitation on MAM discharge at these two sites, (2) develop robust statistical models of MAM discharge using this climate information, and (3) use these models to forecast the impact of snow cover and precipitation changes in the face of uncertain climate change and development in the region, including deforestation [Costa-Cabral et al., 2008] and dam construction [Campbell, 2007; Grumbine et al., 2012], a solid understanding of the environmental controls on water resources in the basin is important for adequately informing risk management and policy development. Recent studies have typically focused on the response of the annual summer flood pulse in the Mekong River to climate change and other factors [e.g., Delgado et al., 2010, 2011; Västilä et al., 2010]. Climate change impacts on dry season flows are relatively understudied, despite the fact that water resources during the dry season play a critical role in regional ecosystem and societal functioning and are a priority focus for resource managers in the region [Campbell, 2007]. And while some studies have tangentially considered dry season flow in the Mekong River as part of broader analyses [e.g., Kiem et al., 2008; Kingston et al., 2011], few have explicitly quantified and discussed modern and potential future climate change impacts on flow during this season. [4] In this study, we analyze the hydrologic controls (precipitation and snow cover) on discharge during the tail end of the dry, low flow season (March–April–May, MAM) in the Lower Mekong Basin (LMB). We focus on two gauging stations bounding the LMB along the main stem of the Mekong River: Vientiane (18°N–103°E) in northern Lao PDR and Kratie (13°N–106°E) in Cambodia. Our objectives are to (1) quantify the impact of Asian snow cover and regional precipitation on MAM discharge at these two sites, (2) develop robust statistical models of MAM discharge using this climate information, and (3) use these models to forecast the impact of snow cover and precipitation changes...
on MAM discharge using climate model projections for the twenty-first century.

2. Materials and Methods

2.1. Analyses

Our methodology is based on empirical analyses of three independent data sets that are then used to develop relatively parsimonious statistical models. This approach is not intended to replace or supersede studies that have addressed related research questions using process based distributed hydrologic models (DHMs) [e.g., Kingston et al., 2011; Kite, 2001]. Rather, our study serves in a complementary capacity, offering different advantages compared to DHM studies. For example, DHMs and other process oriented models often require diverse data inputs that are often not readily available over broad temporal and spatial scales, or may be of unknown or undocumented quality, especially in developing regions. This is especially true for non-standard atmospheric variables for which data coverage is especially sparse, such as radiation, humidity, and cloud cover. Our models and analyses require only three independent, long-term, and quality controlled data sets: snow cover, precipitation, and streamflow. Many process-based models, including DHMs, also require estimates of many poorly known parameters related to the land surface, vegetation, and surface fluxes (e.g., surface roughness, aerodynamic/vegetation resistance, infiltration capacity, etc.). Explicitly accounting for these

Figure 1. Pearson’s correlation coefficients for the relationship between seasonal discharge (March–April–May) at Vientiane and Kratie and (a and b) NOAA satellite snow cover and (c and d) GPCC precipitation. The Mekong watershed is outlined in red, and the regions where the climate predictors are drawn from (see following figures) are indicated by the dashed boxes. Red dots indicate the station gauging locations. Only significant correlations (p ≤ 0.05) are shown.
factors is not necessary in our model: any impact these would have on the relationship between streamflow and snow cover or precipitation is implicitly accounted for in the analyses and model fitting. Finally, from a broader impacts perspective, there is strong evidence that managers, policy makers, and others who make use of climate information in an applied context strongly prefer a portfolio approach incorporating a range of methodologies [Young et al., 2006].

We restrict our statistical analyses to the common time interval (1967–2009) of the three primary data sets we use: discharge measured at two sites on the Mekong River, precipitation, and satellite snow cover. Correlations are Pearson’s r, with a significance threshold of p ≤ 0.05. Our statistical models are multivariate linear regressions, which we calibrate and then validate using a split–sample procedure wherein half the data is withheld from the model calibration and used to test the model predictions (intervals used are 1967–1987 and 1988–2009). For validation statistics, we use validation period $R^2$, reduction of error (RE), and coefficient of efficiency (CE). The RE and CE statistics have theoretical ranges of minus infinity to +1, and are based on a comparison of the model predicted values against a climatological mean value drawn from the calibration (RE) or validation (CE) interval.

Values of $RE$ and $CE > 0$ indicate model skill that exceeds skill from the climatology. Further details on RE and CE, and their use in climate applications, can be found in [Cook et al., 1999]. All analyses and comparisons use simultaneous (lag zero) MAM average values of the various data sets. Additional comparative analyses (not shown), in which variables were shifted to various lead or lag intervals, indicated that strongest statistical relationships were found at zero lag at the seasonal timescale.

Beyond changes in the hydrologic inputs, increases in evapotranspiration driven by expected temperature increases in the future may also lead to reductions in dry season streamflow. We do not consider temperature impacts on streamflow in our analysis, however, because evapotranspiration and streamflow responses to temperature tend to be highly non-linear [Kingston et al., 2011]. This would make it difficult to fit temperature into our relatively simple analysis and modeling framework used in this study. Given this issue, and the overall importance of snow and precipitation inputs for water resources in the Mekong region, we decided to focus our analyses on the impact of changes in these hydroclimate variables, including how they vary across models and individual ensemble members.
significant overbank flow makes it difficult to accurately measure mainstream discharge. These stations are considered to be physically meaningful boundaries for the LMB [Adamson and Bird, 2010].

2.3. Climate Data

Precipitation data are from the Global Precipitation Climatology Centre (GPCC) full data reanalysis version 5 [Beck et al., 2005; Rudolf et al., 1994, 2003, 2005; Rudolf and Schneider, 2004]. The GPCC product is a reanalysis of in situ rain gauge observations, interpolated to a continuous grid across global land areas. The full data set spans 1901–2009, and is available at monthly temporal resolution. These data have been used for a variety of regional and global climate analyses [e.g., Rubel and Kottke, 2010; Wild et al., 2008; Yatagai et al., 2009]. Snow cover data is taken from the NOAA satellite snow cover product, a grid-ded analysis of snow cover across the Northern Hemisphere. These data are based on weekly charts of presence or absence of snow cover at each grid cell [Ramsay, 1998; Robinson et al., 1993], and are in units of percentage of days per month snow covered. The NOAA data set represents the longest temporally continuous and spatially explicit record of Northern Hemisphere snow cover available (1967-present), and has been used in a variety of climate analyses [e.g., Brown, 2000; Brown and Mote, 2009]. Here, we use this product as a proxy for the size of the snowpack and subsequent volume of water that can be supplied to the Mekong River. This assumption is supported by independent analyses demonstrating, for example, that snow depth over the Tibetan plateau is highly correlated with the number of snow covered days [You et al., 2011]. The GPCC precipitation data and the NOAA satellite snow cover product used in this study have a spatial resolution of 1°.

2.4. Climate Projections

For projections of discharge into the future, we use snow cover and precipitation output from the Coupled Model Intercomparison Project version 5 (CMIP5) [Taylor et al., 2012], the latest suite of general circulation model (GCM) experiments being conducted as part of the forthcoming Fifth Assessment Report of the Intergovernmental Panel on Climate Change. We use output from the historical scenario (1950–2005, forced with observed climate forcings) and the RCP 4.5 moderate future emissions scenario (2006–2099) [van Vuuren et al., 2011]. In order to generate a snow cover metric consistent with the NOAA satellite product (representing percentage of days per month a given grid cell was snow covered), we necessarily restrict our analysis to those models that archived daily snow cover for these two scenarios. We further restricted selection to models that archived multiple ensemble members, in order to focus on the forced model responses and allow an assessment of uncertainty. We identified three models that fit these criteria: CanESM2 (Canadian Centre for Climate Modeling and Analysis; 5 ensemble members), MIROC5 (Atmosphere and Ocean Research Institute, The University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology; 3 ensemble members), and MPI-ESM-LR (Max Planck Institute for Meteorology; 3 ensemble members). To account for model mean biases, precipitation and snow cover outputs were
adjusted to observed mean values using the 1967–2005 baseline, the common interval between the historical model simulations and the data. Minimum and maximum values were truncated if necessary to ensure physically realistic values (0 to 1 for snow cover, minimum of 0 for precipitation). Projected future changes in snow cover, precipitation, and Mekong discharge are quantified using the difference in the ensemble mean for two twenty year model periods: 1980–1999 and 2080–2099. Significance is assessed based on a two sided Student’s t-test.

3. Results

3.1. Correlation Analysis

[11] Discharge at Vientiane during MAM is significantly correlated with snow cover over central Asia, including the headwaters region of the Mekong watershed (Figure 1a). Correlations between Kratie and snow cover are weaker, and less spatially extensive (Figure 1b). Streamflow at stations in the lower reaches of the Mekong Basin (such as Kratie) originates primarily from left bank tributaries and local precipitation inputs, and any apparent correlation to the upper basin is likely due to the influence of residual upstream flow. Indeed, discharge at Kratie is highly correlated with Vientiane discharge (Pearson’s r = +0.69, p < 0.001), supporting this explanation for the apparent correlation between Kratie and snow cover.

[12] Discharge at both Vientiane and Kratie is positively correlated with local precipitation. Regions of highest correlation for Vientiane (Figure 1c) are primarily upstream in China and Lao PDR. There is also a region of significant positive correlation over Central Asia, likely reflecting covariation between snow cover and precipitation over this region. Correlations between Kratie and precipitation (Figure 1d) are extensive over much of Indochina, demonstrating the importance of inputs from local precipitation and

Figure 4. Results from the split sample calibration/validation procedure used to develop the regression models for (a and b) Vientiane and (c and d) Kratie. Observed discharge is in blue, the calibration period model prediction is in green, and the validation period model prediction is in red. Inset statistics represent the validation period $R^2$ (RSQ), RE, and CE values.
lower basin tributaries at this site. Apparent correlations between streamflow and precipitation or snow cover outside of the Mekong watershed are likely a consequence of spatial coherency in the precipitation and snow cover data. For example, the correlation decay distance used in the spatial interpolation of precipitation data is typically on the order of several hundred kilometers [Hofstra and New, 2009; Mitchell and Jones, 2005]. Correlations outside of the Mekong watershed therefore likely reflect spatial patterns of precipitation and snow cover variability, rather than direct inputs to streamflow.

The correlation analysis indicates that snow cover and precipitation are potentially skillful predictors for MAM discharge at Vientiane and Kratie. We spatially average snow cover and precipitation time series over the relevant regions of high correlation for each station (Figure 1, black dashed boxes), generating new times series that can be compared against Vientiane (Figure 2) and Kratie (Figure 3) discharge. Correlation between Vientiane discharge and the snow cover time series (Figures 2a and 2c; \( r = +0.59, p < 0.001 \)) is slightly higher than the precipitation correlation (Figures 2b and 2d; \( r = +0.46, p < 0.01 \)). Moving south through the LMB, snowmelt contributions to streamflow are increasingly overwhelmed by inputs from local precipitation and tributaries along the left bank. At Kratie, delimiting the southern extent of the LMB, the correlation with snow cover is much weaker, although still significant (\( r = +0.42, p < 0.05 \)). Instead, Kratie streamflow is strongly correlated with local precipitation (Figure 3; \( r = +0.63, p < 0.001 \)), nearly the same magnitude as the correlation with upstream Vientiane discharge.

### 3.2. Model Calibration and Validation

Discharge at Vientiane appears to be driven by snow cover and local precipitation inputs, and we used the snow cover and precipitation time series in Figure 2 as potential predictors for our discharge model at this location. Discharge at Kratie responds to local precipitation and also integrates flow originating from higher up in the river basin, supported by the significant positive correlation with Vientiane discharge. For our Kratie discharge model, we therefore used the precipitation time series in Figure 3 and upstream discharge at Vientiane as potential predictors. Using the Akaike information criterion (AIC) to determine predictor selection, we found that models for both sites passed a \( \Delta \text{AIC} \) threshold of \( \geq 2 \) for inclusion of both predictors, compared to models that incorporate either single predictor alone.

For our split-sample calibration and validation procedure, we split the data into two intervals (1967–1987 and 1988–2009), alternately calibrating our discharge models using data from one period and validating our model predictions on data from the independent interval. For Vientiane, our regression model explains nearly half the variability in the validation data (Figures 4a and 4b). Notably, the model is also able to reproduce the positive shift toward increased discharge near the start of the twenty-first century, indicating that this feature is likely climate driven rather than a data artifact or the result of non-climate influences. Indeed, both the snow cover and precipitation predictor variables (Figures 2a and 2b) have similar positive shifts around this time. The \( \text{RE} \) and \( \text{CE} \) statistics are also positive, indicating skill beyond climatology. For Kratie, the regression model is even more skillful, with validation period \( R^2 \) values indicating that the model can reproduce over 80% of the variance, depending on the validation period chosen. As with Vientiane, both \( \text{RE} \) and \( \text{CE} \) indicate significant skill beyond climatology. As an alternative model for Kratie, we used the same local precipitation predictor but replaced Vientiane discharge with the snow cover time series that had been previously correlated against Kratie streamflow. This model was less skillful, with validation period \( R^2 \) values ranging from 0.35 to 0.49 and CE values from 0.22 to 0.47, confirming the diminishing importance of snow cover impacts on streamflow in the southern reaches of the LMB. Based on these results, we retained our original Kratie model (precipitation and Vientiane discharge) for the twenty-first century model projections.
Comparing the model validation statistics between our study and previous studies using DHMs is not straightforward. While our study focuses on interannual variability within one seasonal window (MAM), DHM studies typically calibrate and validate on flow in all months, including the seasonal cycle. Beyond this major difference, other studies may also use different time intervals for model validation and calibration, or even different gauging stations. Of the DHM studies we found for the Mekong Basin, Västilä et al. [2010] offers the closest comparison. Using the Variable Infiltration Capacity (VIC) model, the authors of that study compared monthly simulated and observed discharge for Kratie for 1997–2000 and found an $R^2$ value of 0.63. Our own Kratie model compares favorably, validating with $R^2$ values of 0.57 to 0.83, depending on the interval tested. Other DHM studies [Costa-Cabral et al., 2008; Kingston et al., 2011] found, for various gauging stations in the Mekong, Nash-Sutcliffe coefficients (analogous to $RE/CE$) of 0.44 to 0.89. Our $RE$ and $CE$ values generally fall within this range, albeit toward the lower end. Again, however, we note that these studies are comparing against monthly discharge, including the seasonal cycle, and using different stations and time periods for comparison. Given these caveats and differences, our models appear to provide complementary and sufficient predictive skill to allow for their use in exploring future climate impacts on MAM discharge at Vientiane and Kratie.

3.3. Future Projections

[17] From the CMIP5 model runs, we calculated area averaged snow cover and precipitation time series for the equivalent regions used to derive the snow cover and precipitation predictors in Figures 2 and 3. All three models reproduce the seasonality of the annual snow cover and precipitation for these regions (Figure 5), including the seasonal transitions. Two models (MIROC5 and CanESM2) overestimate snow cover during the winter and spring. Significant model precipitation biases occur primarily during the height of the summer monsoon and during the fall monsoon withdrawal, after our season of interest.

[18] In the ensemble mean, all three models show decreasing snow cover in the upper basin over the course of the twenty-first century (Figure 6). Declines are largest in the MIROC5 and MPI-ESM-LR ensembles (−49.8% and −40.2% respectively; p ≤ 0.0001), while CanESM2 projects more modest, but still significant, decreases (−19.9%; p ≤ 0.01). Precipitation in the Vientiane and the Kratie regions are projected to increase in all three models (Figures 7 and 8), and the increases are largest and most significant in the MIROC5 (+37.0%/+9.3%, Vientiane/Kratie) and MPI-ESM-LR (+10.3%/+17.0%, Vientiane/Kratie) simulations. Precipitation
increases at both locations in CanESM2 are less than +5%, and insignificant at the p ≤ 0.05 significance level. We used these climate projections to investigate climate change impacts on MAM discharge through to the end of the twenty-first century (Figures 9 and 10), conducting different experiments to isolate the impact of individual predictors. The Prec+Snow and Prec+Vient scenarios represent the full transient simulations for Vientiane and Kratie respectively, forced with transient model snow cover, precipitation, and modeled Vientiane discharge for 1950–2099. For Vientiane, the alternate experiments are Prec-Only (transient model precipitation and fixed 1950–2000 climatological model snow cover) and Snow-Only (fixed 1950–2000 climatological model precipitation and transient model snow cover). For Kratie, the alternate experiments are Prec-Only (transient model precipitation and fixed 1950–2000 climatological model Vientiane discharge) and Vient-Only (fixed 1950–2000 climatological model precipitation and transient model Vientiane discharge).

For two of the models (CanESM2 and MIROC5, Figure 9a, b), ensemble mean changes in Vientiane discharge (Figure 9) are small (−2.5% and −0.3%, respectively) and insignificant (p > 0.05). Changes in individual ensemble members are also insignificant, ranging from −0.0% to +4.4% (CanESM2) and −1.4% to +1.5% (MIROC5). Ensemble mean Vientiane discharge does significantly decline (−5.1%) in the simulation using MPI-ESM-LR (Figure 9c), and all three ensemble members show significant or marginally significant decreases in discharge: −3.9% (p ≤ 0.09), −4.8% (p ≤ 0.01), and −6.7% (p ≤ 0.05). In all three models, precipitation changes (blue lines) act to increase discharge at Vientiane, while the declines in snow cover (red lines) lead to decreased streamflow. Only in the MPI-ESM-LR ensemble, however, are the snow cover declines able to overwhelm the increased precipitation, leading to a significant decline in the ensemble mean discharge.

As with Vientiane, results for Kratie from the CanESM2 (Figure 10a) and MIROC5 (Figure 10b) ensembles show no significant changes either in the ensemble mean or any individual ensemble member. For CanESM2, changes in individual ensemble member range from −4.7% to +0.7%; for MIROC5 the range is +0.4% to +6.0%. Changes in the ensemble mean for MPI-ESM-LR are similarly small (+3.1%) and insignificant (Figure 10c), although one ensemble member does show large and significant increases in streamflow (+11.0%, p ≤ 0.05). Changes in the other two ensemble members are small and insignificant, however (−0.6% and −1.2%). As with Vientiane, precipitation changes tend to drive increases in streamflow (green lines). In CanESM2 and MIROC5, modeled upstream Vientiane streamflow changes little and has a negligible contribution to long term Kratie streamflow (red lines). For MPI-ESM-LR, however, the significant declines in Vientiane discharge, driven by decreased snow cover and negligible precipitation trends, would act to reduce Kratie streamflow.

4. Discussion and Conclusions

Our results highlight the impact of hydrologic inputs (snow cover and precipitation) on dry season streamflow in the Mekong River. Model validation tests indicate that these variables are robust and skillful predictors that can explain recent trends and shifts in dry season streamflow, including the increases in discharge observed near the turn of the twenty-first century. Results from the future projections using output from a suite of climate models emphasize the importance of considering the spatial heterogeneity of any climate change impacts in the Mekong River Basin, especially across models. For example, despite large and significant declines in Vientiane streamflow in the MPI-ESM-LR projections, changes at Kratie are negligible. This response contrasts sharply with the CanESM2 projections, where responses at Vientiane and Kratie, while insignificant, have similar magnitude and the same sign.

As development continues throughout the Mekong Basin, streamflow during all seasons will also be increasingly influenced by non-climatic factors. Deforestation in the Mekong Basin is widespread, and likely to continue in response to a variety of economic and social drivers [Heinimann et al., 2007; Rowcroft, 2008]. Forest removal can affect surface runoff, soil moisture, and erosion throughout the basin [Costa-Cabral et al., 2008], with expected impacts on total water yield and the seasonal flow distribution in the Mekong River [Adamson et al., 2009]. Dam development on the main stem and Mekong tributaries is also moving at a rapid pace, with dozens of dam projects in China and Lao PDR currently in the construction or planning phase [Grumbine et al., 2012]. All of the main stem dams planned for the lower riparian states, and
most of the dams in China, are ‘run-of-river’ dams, designed to manage electricity demand across a daily cycle with little water retention [Tu, 2011]. And while the expectation is that these dams will shift the seasonal flow from the wet to the dry season [Adamson et al., 2009], it must be emphasized that the primary function of the dams is hydropower generation, rather than flow management, and the ultimate impact on streamflow is uncertain.

[23] Our results have two major implications for water resources in the Mekong Basin. First, reductions in snow cover may reduce discharge from China, where dam development is greatest. With these changes in the background climatology, and with flow contributions from the upper basin during the dry season expected to become increasingly controlled by non-climatic factors, improved information sharing will be critical for maintaining adequate flow for navigation and irrigation downstream. Second, should discharge in the lower basin increase as two models seem to indicate (MIROC5 and MPI-ESM-LR), this may create conflict between rice farming (which is favored by high freshwater flows) and shrimp production (which is not). The balance between these conflicting land uses is maintained by a set of defined agricultural zones and a system of sluice gates to manage fresh and brackish water flows [Hoanh et al., 2003; Dung et al., 2009]. An increase in dry season discharge in the lower basin—indeed independently of any speculated increase due to hydropower development—is evidence that rice irrigation in the dry season may remain feasible in many areas of current production for the decades to come. Such insight can be of value both at the planning level, as the

Figure 9. Ensemble average simulated discharge for Vientiane for the three GCMs: (a) CanESM2, (b) MIROC5, and (c) MPI-ESM-LR. Prec+Snow represents a scenario with full transient model projections of precipitation and snow cover. Prec-Only is forced by transient model precipitation projections and fixed twentieth-century climatological model snow cover (averaged over 1950–2000). Snow-Only is forced by fixed twentieth-century climatological model precipitation (averaged over 1950–2000) and transient model snow cover. All curves are ensemble means, smoothed by averaging across a 5-year moving window. Dashed line indicates the model mean for 1950–2000.

Figure 10. Ensemble average simulated discharge for Kratie for the three GCMs: (a) CanESM2, (b) MIROC5, and (c) MPI-ESM-LR. Prec+Vient represents a scenario with full transient model projections of precipitation and simulated discharge at Vientiane. Prec-Only is forced by transient model precipitation projections and fixed twentieth-century climatological modeled discharge at Vientiane. Vient-Only is forced by fixed twentieth-century climatological model precipitation (averaged over 1950–2000) and transient simulated discharge at Vientiane. All curves are ensemble means, smoothed by averaging across a 5-year moving window. Dashed line indicates the model mean for 1950–2000.
established agricultural zoning is revisited in the future, as well as at the local commune, village, and household level as farmers living near the shrimp-rice boundaries consider how best to invest for their futures.

Our statistical approach provides a clear empirical link between snow cover, precipitation, and main stem dry season discharge in the upper and lower reaches of the LMB. It provides insight into the ways in which climatic factors may drive divergent streamflow outcomes across the LMB in coming decades, which is important context in which to consider the impact from regional development, including land cover and dam construction. Natural resource decision-making benefits from portfolio approaches to understanding an issue [Young et al., 2006], and this study should provide a useful complement to existing simulation-based, case study, and narrative planning approaches for water resources in the Mekong River Basin.

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