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Research papers

Evaluation of climate modeling factors impacting the variance of streamflow

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ABSTRACT

The present contribution quantifies the relative importance of climate modeling factors and chosen response variables upon controlling the variance of streamflow forecasted with global climate model (GCM) projections, which has not been attempted in previous literature to our knowledge. We designed an experiment that varied climate modeling factors, including GCM type, project phase, emission scenario, downscaling method, and bias correction. The streamflow response variable was also varied and included forecasted streamflow and difference in forecast and hindcast streamflow predictions. GCM results and the Soil Water Assessment Tool (SWAT) were used to predict streamflow for a wet, temperate watershed in central Kentucky USA. After calibrating the streamflow model, 112 climate realizations were simulated within the streamflow model and then analyzed on a monthly basis using analysis of variance. Analysis of variance results indicate that the difference in forecast and hindcast streamflow predictions is a function of GCM type, climate model project phase, and downscaling approach. The prediction of forecasted streamflow is a function of GCM type, project phase, downscaling method, emission scenario, and bias correction method. The results indicate the relative importance of the five climate modeling factors when designing streamflow prediction ensembles and quantify the reduction in uncertainty associated with coupling the climate results with the hydrologic model when subtracting the hindcast simulations. Thereafter, analysis of streamflow prediction ensembles with different numbers of realizations show that use of all available realizations is unneeded for the study system, so long as the ensemble design is well balanced. After accounting for the factors controlling streamflow variance, results show that predicted average monthly change in streamflow tends to follow precipitation changes and result in a net increase in the average annual precipitation and streamflow by 10% and 11%, respectively, for the wet, temperate watershed.

1. Introduction

Within the hydrologic sciences community, increased emphasis is being placed on gaining an understanding of how climate change will impact hydrologic processes and streamflow throughout the streams and rivers of the world. Specifically, the GCM projections of increased and decreased precipitation in wet and dry regions, respectively, are of great interest regarding how such occurrences could produce long term changes in regional water balances. Notwithstanding the importance of forecasted streamflow, climate scientists are quick to point out the inherent uncertainty associated with GCM projections due to their underlying assumptions and parameterizations. Further, as GCM projections are downscaled and propagated through hydrologic models, the hydrologic community has cautioned the use of the reliability of forecasted streamflow results due to the propagation of uncertainty derived from climate projections as well as the multiple levels of uncertainty that can be introduced throughout the hydrologic modeling process. Our motivation in this contribution is to broaden understanding of how factors, termed herein 'climate modeling factors', inherent of climate and hydrologic model coupling as well as forecasted streamflow response variables impart uncertainty within streamflow projections, and to apply our new knowledge for predicting future streamflow in a wet, temperate stream.

Studies that investigate uncertainty introduced during streamflow forecasting with GCM projections have become prevalent in the hydrologic literature over the past decade (e.g., Tu, 2009; Neupane and Kumar, 2015a,b). Investigations of uncertainty have for the most part been much more well received by scientists as

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compared to specific results of forecasted streamflow, the latter of which are somewhat viewed as a moving target. Uncertainty studies of forecasted streamflow have focused on a number of factors that have been found to introduce variability of results (see Table 1). Emphasis has been placed on uncertainty from the choice of GCM and emission scenarios, and hence showed a need for numerous climate forcings in hydrologic predictions due to model assumptions and uncertainty of fossil fuel emissions over the next 50 years (Sheshukov et al., 2011; Harding et al., 2012). A number of studies have focused on the choice of statistical downscaling as compared to the more physically-based dynamical downscaling of GCM results for input to hydrologic models, and emphasized the differences that can result in streamflow prediction dependent upon the downscaling method (Chen et al., 2011; Mejia et al., 2012; Chen et al., 2012; Al-Mukhtar et al., 2014; Fatichi et al., 2014). Further, questions have been raised regarding uncertainty as well as stationarity assumptions introduced by precipitation and temperature bias correction techniques (Teutschbein and Seibert, 2012).

One potential uncertainty impacting streamflow forecasts that has not been thoroughly investigated is the choice of climate project phase, defined here to indicate the difference in the same GCMs between different model intercomparison projects. The project phase factor requires investigation of how advancement in climate model sophistication and emission scenario projection might impact streamflow uncertainty. Specifically, recent completion of the Coupled Model Intercomparison Phase 5 (CMIP5) provides a new dataset of climate forcings relative to CMIP3. CMIP5 uses the Representative Concentration Pathways (RCP) as the emission scenarios which represent a newer advancement of the future development in greenhouse gas emission. In addition, CMIP5 uses the newest versions of GCMs for its projections. CMIP3 represents the extensively published phase three results from GCMs and uses the Spatial Report on Emission Scenarios (SRES). Both project phases have reported statistically downscaled climate model results and have made use of bias-correction and spatial disaggregation and daily bias-correction and constructed analogs statistical downscaling methods for precipitation and minimum and maximum surface air temperature; and the North American Regional Climate Change Assessment Program (NARCCAP) has published extensive results of dynamically downscaled GCM results that can be compared to the statistical downscaling reported from CMIP3. In particular, the new CMIP5 has been promoted as a new information module for climate change predictions but at the same time has not been quantified as necessarily a more reliable source of climate projections compared to CMIP3 (Brekke et al., 2013). Uncertainty introduced by CMIP5 into hydrologic predictions remains relatively untested, and one contribution of this paper is testing the importance of project phase upon streamflow predictions.

Results of past studies have shown the potential of 'climate modeling factors', including GCM type, emission scenario, downscaling method, and bias correction technique, to introduce uncertainty in forecasted streamflow for some case studies (Table 1). In addition to these climate modeling factors, project phase will be investigated herein. We also take the next logical step in uncertainty analysis and strive to investigate the relative importance of each climate modeling factor imparting uncertainty upon forecasted streamflow. No studies have attempted to quantify the relative importance of the different climate modeling factors impacting the variance of streamflow forecasted with GCM projections. It is well recognized that the first decade of this fairly new branch of hydrologic research (see Table 1) has relied on gaining an understanding of the factors that might impact the results of forecasted streamflow. However, at the same time, we recommend a shift towards uncertainty analyses that aims to partition variance into different factors in order that the most controlling factors imparting uncertainty are included in streamflow forecast analyses. It is recognized that the partitioning of variance for streamflow forecasts is not a narrow task and likely numerous permutations are needed that vary climate type in terms of precipitation (e.g., wet regions, dry regions) and temperature (e.g., tropics, temperate, frigid), spatial scale (e.g., catchment, watershed, basin), projected target dates (e.g., 2050, 2100), landscape characteristics (e.g., lowland agricultural, mountainous forested), and streamflow response (e.g., baseflow, mean streamflow, flood extremities). Nevertheless, the present study works towards this broad goal for the first time to our knowledge by analyzing the uncertainty imparted upon streamflow forecasts by considering a suite of climate modeling factors, including GCM, project type (i.e., CMIP3 versus CMIP5), emission scenario, downscaling method (i.e., statistical versus dynamic), and bias correction. We cast this uncertainty investigation within a specific hydrologic model analysis that focuses on forecasting mean streamflow for 2046–2065 for a lowland agricultural watershed within a temperate, wet region.

In addition to investigating climate modeling factors impact upon forecasted streamflow, we also investigate the choice of the future streamflow response variable within hydrologic model analysis. We argue that as watershed managers begin to apply streamflow forecasts in their planning and decision making pro-

Table 1
Review of climate modeling factors investigated in previous studies.

Author	Total realizations	Project	GCMs	Emission scenario	Downscaling method	Bias correction	Response variable
Tu (2009)	3	$CMIP3_{equiv}$	1	A1B, A2, and B1	Not performed	No	ΔQ_{F-H}
Chen et al. (2011)	6	$CMIP3_{equiv}$	1	A2	Statistical and dynamical	Yes	Q_F
Sheshukov et al. (2011)	15	$CMIP3_{equiv}$	15	A2	Statistical	No	Q_F, ΔQ_{F-H}
Farmarzi et al. (2012)	18	$CMIP3_{equiv}$	5	A1F1, A1B, A2, and B1	Statistical	No	Q_F, ΔQ_{F-O}
Ficklin et al. (2012)	32	CMIP3	16	B1 and A2	Statistical	No	Q_F, ΔQ_{F-O}
Harding et al. (2012)	112	CMIP3	16	A2, A1B, B1	Statistical	No	Q_F, ΔQ_{F-H}
Mejia et al. (2012)	2	CMIP3	1	NA (historical period only)	Statistical and dynamical	No	Q_H
Chen et al. (2012)	4	$CMIP3_{equiv}$	3	A2	Statistical and dynamical	Yes	Q_F, ΔQ_{F-O}
Chien et al. (2013)	28	CMIP3	9	A1B, A2, and B1	Statistical	Yes	Q_F, ΔQ_{F-H}
Ficklin et al. (2013)	16	CMIP3	16	A2	Statistical	No	Q_F, ΔQ_{F-O}
Guimberteau et al. (2013)	24	$CMIP3_{equiv}$	8	A2, A1B, B1	Statistical	No	ΔQ_{F-O}
Park et al. (2013)	2	$CMIP3_{equiv}$	1	A2 and B2	Statistical	No	Q_F, ΔQ_{F-O}
Al-Mukhtar et al. (2014)	12	$CMIP3_{equiv}$	1	A1B	Statistical and dynamical	Yes	ΔQ_{F-O}
Fatichi et al. (2014)	34	CMIP3	13	A1B	Statistical and dynamical	Yes	Q_F, ΔQ_{F-H}
Wang et al. (2014)	12	CMIP3	4	A1B, A2, and B1	Statistical	Yes	ΔQ_{F-O}
Neupane and Kumar (2015a)	48	CMIP3	16	A1B, A2, and B1	Statistical	No	ΔQ_{F-O}
Neupane and Kumar (2015b)	48	CMIP3	8	A1B, A2, and B1	Statistical	No	ΔQ_{F-O}

Note: $CMIP3_{eqiuv}$ means that the model version or downscaling method differed (i.e., NARCCAP) than those in the CMIP3 project but the used model and emission scenarios were the same.