Meteorologische Zeitschrift, Vol. 19, No. 4, 341-346 (August 2010)

Article

Streamflow in the upper Mississippi river basin as simulated by SWAT driven by 20th Century contemporary results of global climate models and NARCCAP regional climate models

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(Manuscript received October 10, 2009; in revised form March 10, 2010, accepted May 3, 2010)

Abstract

We use Soil and Water Assessment Tool (SWAT) when driven by observations and results of climate models to evaluate hydrological quantities, including streamflow, in the Upper Mississippi River Basin (UMRB) for 1981–2003 in comparison to observed streamflow. Daily meteorological conditions used as input to SWAT are taken from (1) observations at weather stations in the basin, (2) daily meteorological conditions simulated by a collection of regional climate models (RCMs) driven by reanalysis boundary conditions, and (3) daily meteorological conditions simulated by a collection of global climate models (GCMs). Regional models used are those whose data are archived by the North American Regional Climate Change Assessment Program (NARCCAP). Results show that regional models correctly simulate the seasonal cycle of precipitation, temperature, and streamflow within the basin. Regional models also capture interannual extremes represented by the flood of 1993 and the dry conditions of 2000. The ensemble means of both the GCM-driven and RCM-driven simulations by SWAT capture both the timing and amplitude of the seasonal cycle of streamflow with neither demonstrating significant superiority at the basin level.

Zusammenfassung

Das „Soil and Water Assessment Tool" (SWAT), angetrieben mit Beobachtungen, und die Ergebnisse von Klimamodellen werden benutzt, um hydrologische Größen, einschließlich Abfluss, im oberen Einzugsgebiet des Mississippi (UMRB) für die Zeit 1981–2002 mit beobachteten Abflussdaten zu vergleichen. Der tägliche meteorologische Zustand für die Eingabe in das SWAT wird aus (1) Beobachtungen an Wetterstationen im Einzugsgebiet, (2) Simulationen mehrerer regionaler Klimamodelle (RCMs), angetrieben mit Randdaten aus Reanalysen, und (3) Simulationen mehrerer globaler Klimamodelle (GCMs) entnommen. Die Ergebnisse der regionalen Modelle werden dem Datenarchiv von NARCCAP (North American Regional Climate Change Assessment Program) entnommen. Die Vergleiche zeigen, dass die Regionalmodelle den Jahreszeitengang von Niederschlag, Temperatur und Abfluss im Einzugsgebiet korrekt wiedergeben können. Die regionalen Modelle konnten auch die Extremereignisse, die Flut in 1993 und die Trockenperiode in 2000, simulieren. Die mit den Ensemblemittel von GCMs und RCMs angetriebenen SWAT-Simulationen geben sowohl den zeitlichen Verlauf, als auch die Amplitude des Jahreszeitengangs des Abflusses wieder, wobei, bezogen auf das Einzugsgebiet, keines der beiden Ensemblemittel eindeutig bessere Ergebnisse als das andere liefert.

1 Introduction

Regional climate models (RCMs), having higher spatial resolution than global climate models (GCMs), can be expected to produce spatial refinement (over global model results) of climate details in regions of high topographic variability (e.g., mountains, coastal areas, large inland water bodies; DIFFENBAUGH et al., 2004; LEUNG et al., 2004) or in regions of known large climate gradients (e.g., Sahel; cf. CLARK et al., 2001; ABIODUN et al., 2008). But do they improve on GCM results in regions where such variability is low? The Upper Mississippi River Basin (UMRB), a region of relatively low topographic and climate variability, is a suitable region to explore this question. We herein use GCMs and RCMs to simulate climate and to drive a hydrological model to simulate streamflow at the basin-scale (but not sub-basin scale) for the last decades of the 20th century (20C).

Streamflow is an amplifier of fluctuations in climate extremes and climate variability as well as long-term trends in climate variables. Modest changes in rainfall or snowfall characteristics can have significant societal impacts due to the resulting changes in streamflow. For instance, JHA et al. (2004) found that a 21 % increase in precipitation in a future scenario (2040s) climate leads to a 50 % increase in streamflow in the UMRB. Similarly, for an Iowa location for which extensive subsurface agricultural drainage pipe (tile) has been installed, a separate study (SINGH et al., 2009) using two RCMs showed that increases in precipitation of 24 % and 32 % (and accompanying warming) leads to drainage-tile flow increases of 35 % and 80 %, respectively. Land use in

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0941-2948/2010/0464 $ 2.70

DOI 10.1127/0941-2948/2010/0464

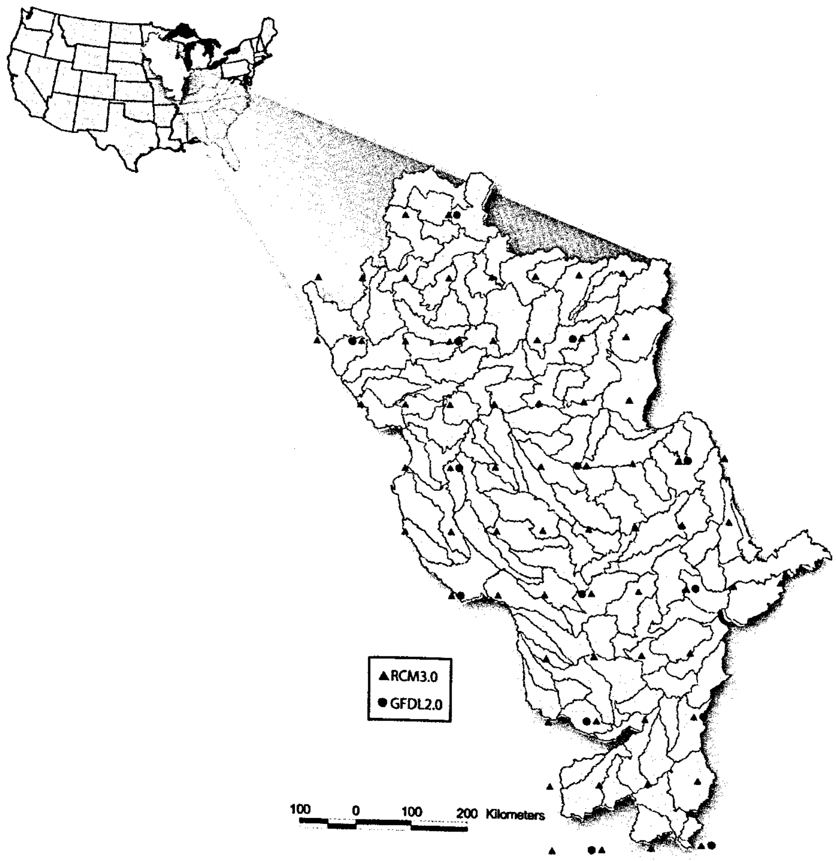

Figure 1: Location of the study domain (Upper Mississippi River Basin), subbasin delineation for SWAT simulations, and spatial resolution of climate model grid/data points.

the form of urbanization, agricultural activity, subsurface drainage, and use of perennial vegetation has major impact on how precipitation translates into streamflow. Recent and projected future changes in extreme climate events and long-term trends call for improved methods for understanding future streamflow and its societal impact.

We use the SWAT model (ARNOLD et al., 1998) driven by output of climate models to evaluate streamflow and other hydrological quantities in the UMRB in the last two decades of the 20$^{\text{th}}$ century in comparison to observed streamflow. The UMRB-SWAT modeling framework developed at the Center for Agricultural and Rural Development at Iowa State University in Ames, Iowa, USA has been successfully applied to climate change studies that include various climate models (JHA et al., 2004; TAKLE et al., 2006, 2009; LU et al., 2010). This modeling setup was used to evaluate the 20$^{\text{th}}$ century contemporary climate results produced by the global and regional climate models. Climatic inputs to SWAT are provided by daily meteorological quantities observed at weather stations within the basin as well as daily meteorological conditions simulated by ten GCMs and six RCMs driven by reanalysis boundary conditions.

2 Description of the models

Global climate models (GCMs)

Meteorological data input to SWAT includes daily values of maximum and minimum temperature, total precipitation, mean wind speed, total solar radiation, and mean relative humidity. In the current IPCC Data Archive (www-pcmdi.llnl.gov/), ten global climate models (including the two versions of models from the Geophysical Fluid Dynamics Laboratory; Table 1) provide daily values of these quantities. Data of the ten models for the 20$^{\text{th}}$ century contemporary climate (20C) for the period 1961–2000 with historical greenhouse gas concentrations (20C3M) are used in this study for SWAT simulations.

Regional climate models (RCMs)

Meteorological data from six RCMs reporting to the archive of the North American Regional Climate Change Assessment Program (NARCCAP, www.narccap.ucar.edu)

Table 1: Global climate models used in the SWAT simulations.

Model ID	Institution	Model Name	Lon x Lat Resolution
M01	Bjerknes Centre for Climate Research (Norway)	BCCR_BCM2.0	2.8° x 2.8°
M02	Canadian Centre for Climate Modelling & Analysis	CCCMA_CGCM3.1	3.8° x 3.7°
M03	Météo-France / Centre National de Recherches Météorologiques (France)	CNRM_CM3	2.8° x 2.8°
M04	CSIRO Atmospheric Research (Australia)	CSIRO_MK3.0	2.8° x 2.8°
M05	NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL_CM2.0	2.5° x 2.0°
M06	NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL_CM2.1	2.5° x 2.0°
M07	Center for Climate System Research (Japan)	MIROC3.2_MEDRES	2.8° x 2.8°
M08	Meteorological Institute of the University of Bonn (Germany)	MIUB_ECHO_G	3.8° x 3.7°
M09	Max Planck Institute for Meteorology (Germany)	MPI_ECHAM5	1.9° x 1.9°
M10	Meteorological Research Institute (Japan)	MRI_CGCM2.3.2A	2.8° x 2.8°

Table 2: Regional climate models used in the SWAT simulations.

Model ID	Institution Providing Simulations	Model Name
CRCM	Ouranos Consortium on Regional Climatology and Adaption to Climate Change	Canadian RCM
HRM3	Met Office Hadley Centre	Hadley Regional Model 3
MM5I	Iowa State University	NCAR/Penn State Mesoscale Model 5
WRFP	Pacific Northwest National Laboratories	Weather Research & Forecasting Model
RCM3	University of California – Santa Cruz	ICTP Regional Climate Model Version 3
ECPC	Experimental Climate Prediction Center, Scripps Oceanographic Institution	Experimental Climate Prediction Center Regional Spectral Model (RSM)

are used to drive the SWAT model. The descriptions of the RCMs used in this study are listed in Table 2 and further described at www.narccap.ucar.edu. These RCMs are driven with the NCEP Reanalysis II data. Simulations for the period 1981–2003 are used in this study. All the RCMs are run at a grid spacing of 50 km.

Hydrologic model

The SWAT model operates on a daily times step and is capable of modeling the impact of different land use and management practices as well as different weather patterns, such as potential future climate change, on hydrology and water quality of the basin. SWAT is a long-term simulation model that is not suitable to study streamflow extremes on a daily basis. Major model components include hydrology, weather, soil temperature, crop growth, nutrient, bacteria, and land management. In SWAT, a basin is divided into several subbasins, which are further delineated by hydrologic response units (HRUs) that consist of homogeneous soil, land use and management characteristics. The HRUs represent percentages of a subbasin area and thus are not spatially defined in the model. The water balance of each HRU is represented by four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer. Flow generation, sediment yield and pollutant loadings are summed across all HRUs within a subbasin, and the resulting values are then routed through channels, ponds, and/or reservoirs to the basin outlet. NEITSCH et al. (2002) provide detailed documentation of the current SWAT 2005 model.

Measured stream flows during 1989–1997 at USGS gauge station 05587450 on the Mississippi River near Grafton, IL were used to calibrate SWAT. The model was calibrated by minimizing the difference between measured and simulated stream flow at Grafton. Since

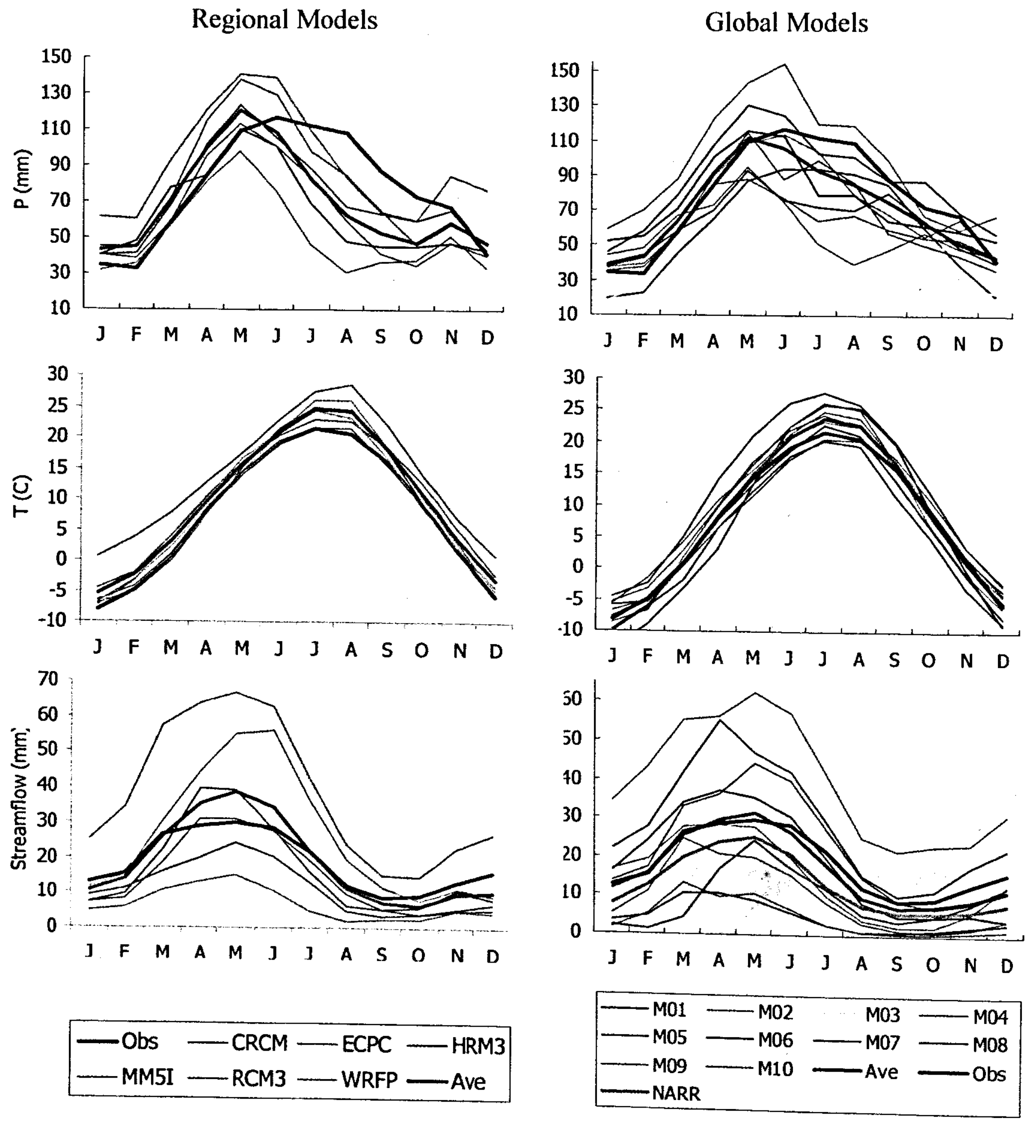

Figure 2: The domain (UMRB) and period (multiple years) averaged monthly means of the daily precipitation, daily mean temperature, and SWAT-simulated streamflow.

only total flow data were available, no attempt was made to calibrate baseflow and surface runoff independent of total stream flow. The flow-related model parameters such as runoff curve number, soil evaporation compensation factor, plant uptake compensation factor, re-evaporation coefficient, and groundwater delay were adjusted from the model initial estimates to fit simulated flows to the observed values. Further details of the calibration and validation applicable to this study are given in JHA et al. (2006).

3 Description of the study domain and modeling framework

The UMRB extends from the source of the Mississippi river at Lake Itasca in Minnesota to a point just north of Cairo, Illinois (Figure 1). The total drainage area is nearly 492,000 km^2, which lies primarily in parts of Minnesota, Wisconsin, Iowa, Illinois, and Missouri. Cropland and pasture are the dominant land uses in the UMRB, which together are estimated to account for over 60 % of the total area (NAS, 2000). The shift into agri-culturally dominated ecosystems from tallgrass prairies, oak savannas and hardwood forest ecosystems (prior to European settlement) in the UMRB has greatly impacted landscape response to precipitation-driven runoff and sediment loss in the region, as determined by studies of the alluvial stratigraphy of the Mississippi stream system (KNOX, 2001).

The UMRB-SWAT modeling system incorporates GIS capability, survey and laboratory input databases including topography, land cover, land management practices, weather, point sources, reservoirs, wetlands, streamflow and water quality variables, and economic costs of establishing land management practices (GASSMAN et al., 2006). The setup was successfully calibrated and validated for basin hydrology, streamflow, and nutrients including nitrate nitrogen and phosphorus (JHA et al., 2006). This integrated modeling system is fully capable of simulating different land management practices, land use land cover changes, and/or potential future climate change to evaluate the impacts of these changes on UMRB water quality.

We analyzed UMRB streamflow simulated by SWAT when GCMs and RCMs were used to provide the climate input. Figure 1 also depicts the grid point locations for a typical GCM and RCM. It should be noted that the RCMs have about 130 nodes in the basin whereas the global models have about an order of magnitude fewer.

4 Results

We use daily output of GCM and RCM precipitation and temperature to compute monthly and basin-average precipitation and temperature (Figure 2) and as input to SWAT to predict streamflow (bottom graphs in Figure 2) for the period 1981–2003. RCMs have a sharper spring peak in precipitation than GCMs and observations, and both sets have their ensemble means occurring a month too early. Oddly, all RCMs simulate an erroneous secondary maximum in November (likely a common response to a feature of the reanalysis boundary conditions used to drive all models). Both sets have too much precipitation for December through May and too little from June through November, with RCM departures from observed being greater than those for GCMs. RCMs tend to have more of a warm bias, while GCMs tend to have a cold bias of smaller magnitude. Both sets of models have excessive amplitude of the seasonal cycle of streamflow as might be expected from the monthly precipitation results, with first half of the year being too high and second half too low. Observations have a broad peak from April through June with peak maximum value in April, whereas RCMs give a similar timing of a broad peak but with maximum in May. The ensemble mean of the GCM-driven simulations by SWAT captures both the timing and amplitude of the seasonal cycle. Despite the wide range in annual mean streamflow simulated by the individual global and regional models, both of the respective ensembles have means quite close to the observed mean and the major characteristics of the seasonal variation (Figure 3).

The time series of annual streamflow as simulated by SWAT with RCM input (Figure 4) reveals that each model tends to have a bias that is constant in sign and in its proportion to magnitude of the streamflow: a model that is biased high is high in almost every year by about the same fraction of the observed for that year. The RCMs provide conditions leading to a wide range of streamflow. Despite high variance in absolute streamflow, all models except ECPC capture the interannual variability represented by the extreme low flow of 1988 and the very high flow in 1993.

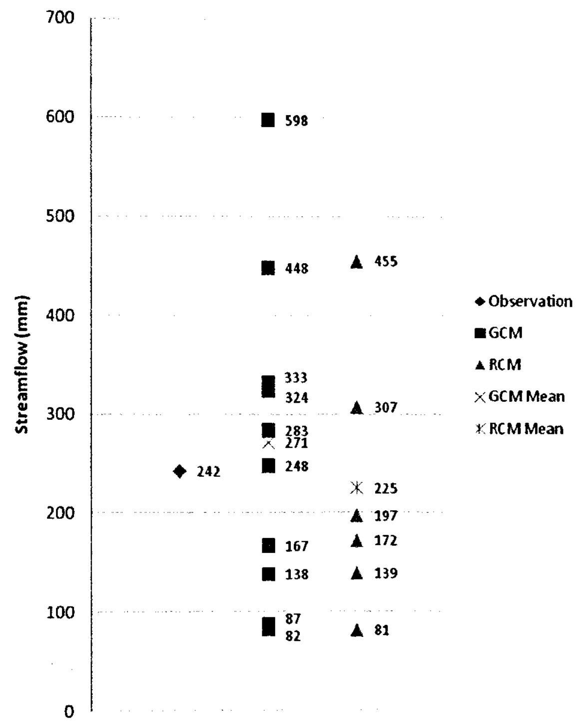

Figure 3: Average annual streamflow simulated by SWAT and driven by climate data from observation (1981–2004) climate, 10 GCMs (1961–2000), and 6 RCMs (1981–2003).

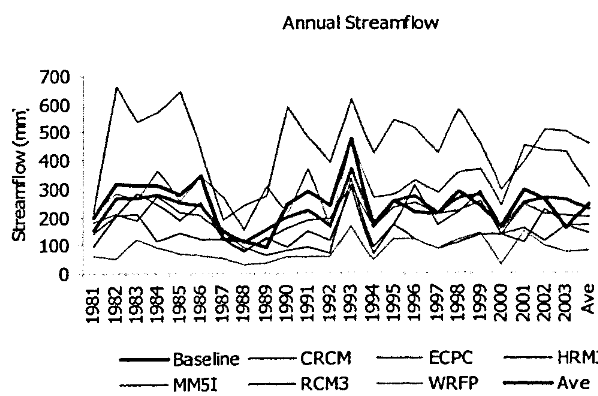

Figure 4: Interannual streamflow simulated by SWAT with input provided by RCMs.

5 Summary

This study explores the skill of global and regional climate models for simulating basin-scale climate and the hydrological cycle in a region of low topographic variability. Do RCMs provide higher skill in representing hydrological properties of the UMRB than GCMs when used to drive SWAT? Figure 3 suggests perhaps yes for representing annual flow, but the high variance of both model ensembles indicates there is low significance to any RCM superiority. Simulation of seasonal streamflow as shown in Figure 2, reveals high spread of the members of both model ensembles, with the means tracking the seasonal variations reasonably well. The GCMs simulate the annual peak slightly better than the RCMs but again the high variance reduces confidence in identifying superior skill.

Previous studies indicate a clear added value of RCMs in regions of complex terrain due to improved spatial distribution of precipitation driven by terrain forcing. The UMRB, by contrast, is quite large and relatively flat, so terrain forcing is minimal. The ability of RCMs to resolve finer scale atmospheric dynamical processes also may provide less advantage for this particular application because the temporal and spatial integration of the network of streams in this region may mask the impact of higher resolution (in both space and time) of precipitation. We are exploring whether resolution advantages may emerge at the subbasin level when highly heterogeneous nitrate loading is provided over the basin, but this is not relevant to the current paper.

Acknowledgments

We acknowledge the North American Regional Climate Change Assessment Program (NARCCAP) including the climate modeling groups and the NCAR/LLNL archiving teams (www.narccap.ucar.edu/about/participants.html) for providing the data used in this publication. NARCCAP is funded by the US National Science Foundation, US Department of Energy, the National Oceanic and Atmospheric Administration (NOAA) and the U. S. Environmental Protection Agency Office of Research and Development. Partial support for this work was provided by USDA National Research Initiative Grant #20063561516724 and also by the US DOE Office of Science (BER) through the Midwestern Regional Center of the National Institute for Climate Change Research (NICCR) under grant #MTU050616Z11.

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