# 9.9 CLIMATE CHANGE IMPACTS ON THE HYDROLOGY OF THE UPPER MISSISSIPPI RIVER BASIN AS DETERMINED BY AN ENSEMBLE OF GCMS

Eugene S. Takle[1], Manoj Jha,[1] Christopher J. Anderson[2], and Philip W. Gassman[1]
[1]Iowa State University, Ames, IA
[2]NOAA Earth System Research Laboratory Global Systems Division Forecast Research Branch,
NOAA/ESRL/GSD/FRB, Boulder, CO

## 1. INTRODUCTION

Stocker and Raible, (2005) and Wu et al., (2005) recently have suggested that the hydrological cycle is accelerating in high latitudes in the Northern Hemisphere. Detailed evaluation of the spectrum of precipitation events for the central US (Groisman, et al, 2005) reveal that the occurrence of extreme intense precipitation events has increased over the twentieth century. Better understanding of changes of the hydrological cycle and assessments of local and regional impacts of changes in the hydrological cycle in future climates require improved capabilities for modeling the hydrological cycle and its individual components at the subwatershed level.

Takle et al. (2005) report a preliminary study to determine the ability of global models to produce suitable input for the Soil and Water Assessment Tool (SWAT) watershed model (Arnold and Fohrer, 2005) to simulate components of the hydrological cycle in the Upper Mississippi River Basin (UMRB). Jha et al, (2004) showed that for the UMRB SWAT provided good results for annual streamflow while having larger uncertainty of monthly values, but it is not clear whether either spatial or temporal refinement of global model results is warranted for simulating streamflow for this watershed. Use of data from global climate models directly is an alternative to using regional climate models or statistical models to downscale global results. Multi-model ensembles have provided (at least for one region and one period) a reliable source of weather data for assessing streamflow (Takle et al., 2005).

## 2. BASIN

The UMRB has a drainage area of 447,500 km$^2$ up to the point just before the confluence of the Missouri and Mississippi Rivers near Grafton, Illinois (Figure 1). Land cover in the basin is diverse and includes agricultural lands, forests, wetlands, lakes, prairies, and urban areas. The river system supports commercial navigation, recreation, and a wide variety of ecosystems and is an important pathway for moving grain out of the US Midwest.

Figure 1. The Upper Mississippi River Basin and delineated subwatersheds.

The basin is divided into 119 subwatersheds for adaptation to SWAT, with each subwatershed being subdivided in hydrological response units (HRUs) such that the basin consists of 474 HRUs. One hundred eleven weather stations relatively uniformly distributed throughout the basin provide observed climate data on approximately the scale of the subwatersheds as input to the hydrological model for simulating baseline streamflows. Details of land use, soils, and topography data for the UMRB are provided in Jha et al. (2004). Our study domain lacks fine-scale orographic features that otherwise would surely compromise the ability of GCMs to describe the spatial distribution of hydrological processes over a region containing only a few GCM grid points. Therefore, the region provides a testbed for evaluating the role of model resolution independent of orographic forcing.

---

* *Corresponding author address*: Eugene S. Takle, 3010 Agronomy Hall, Iowa State University, Ames, IA 50011. gstakle@iastate.edu

## 3. MODELS, RESOLUTION, AND BIAS

### 3.1 *Hydrological Model*

SWAT (Arnold and Fohrer, 2005) is a continuous time, long-term, watershed scale hydrology model with capability to also simulate water quality model. The model was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The model is based on physical principles and uses information on soils, management (e.g., tillage, chemicals applied, crop type) as input. It operates on a daily time step and is computationally efficient, but is not designed to simulate detailed, single-event flood routing.

Subdivision of the watershed into HRUs enables SWAT to reflect differences in evapotranspiration for various crops and soils. Calculated values of flow, sediment yield, and non-point-source loadings for each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Upland components include hydrology, weather, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, and land and water management. Stream processes considered in SWAT include channel flood routing, channel sediment routing, and nutrient and pesticide routing and transformation. The ponds and reservoirs components contain water balance, routing, sediment settling, and simplified nutrient and pesticide transformation routines.

Meteorological input to SWAT includes daily values of maximum and minimum temperature, total precipitation, mean wind speed, total solar radiation, and mean relative humidity. The hydrologic cycle as simulated by SWAT at the HRU level is based on the balance of precipitation, surface runoff, percolation, evapotranspiration, and soil water storage. Values of total daily precipitation, provided to SWAT from either models or observations, is classified as rain or snow on the basis of daily average temperature.

The snow cover is allowed to be non-uniform due to shading, drifting, topography and land cover and is allowed to decline non-linearly based on an areal depletion curve. Snowmelt, a critical factor in partitioning between runoff and baseflow, is controlled by the air and snow pack temperature, melting rate, and areal coverage of snow. On days when the maximum temperature exceeds 0ºC, snow melts according to a linear relationship of the difference between the average snow pack maximum temperature and the base or threshold temperature for snowmelt. The melt factor varies seasonally, and melted snow is treated the same as rainfall for estimating runoff and percolation.

SWAT simulates surface runoff volumes for each HRU using a modified SCS curve number method (USDA Soil Conservation Service, 1972). Further details can also be found in the SWAT User's manual (Neitsch et al., 2002). The version of SWAT used to produce results reported herein is the same model used by Jha et al. (2004) calibrated for the UMRB baseline conditions.

### 3.2 *Global Climate Models*

At the time this study was in progress there were meteorological conditions, including daily values needed for our simulations of future scenarios, available from seven global climate models (see Table 1) in the IPCC Data Archive (PCMDI, 2005). While not spanning the full range of model variability and giving disproportionate weight to models from two laboratories for which two model versions were available, the results do provide a preliminary view of the hydrologic cycle components resulting from direct use of data generated by multiple GCMs.

Takle et al. (2005) found that streamflow data resulting from the GCM ensemble, consisting of models used here plus two more, were serially uncorrelated at all lags and formed unimodal distributions, suggesting that the data may be modeled as independent samples from an identical normal distribution. The test of the hypothesis of zero difference between mean annual streamflow of the pooled GCM/SWAT and OBS/SWAT results gave a p-value of 0.5979, suggesting that use of GCM ensemble results may provide a valid approach for assessing annual streamflow in the UMRB.

We use model output from runs of seven of the nine models examined by Takle et al. (2005), i.e., those having output for the twenty-first century (21C) A1B emission scenario (IPCC, 2001) for the period 2082-2099. Biases in hydrological cycle components produced by the GCMs in combination with SWAT are calculated from comparisons with a subset (1961-2000) of the GCM 20th century runs for which streamflow measurements were available.

**Table 1. Global models used in the SWAT-UMRB simulations (see Takle et al., 2005 for model details).**

| Country | Model Name | Lon x Lat Resolution |
|---|---|---|
| NOAA/GFDL | GFDL-CM 2.0 | 2.5° x 2.0° |
| Center for Clim. Sys. Res (Japan) | MIROC3.2(medres) | 2.8° x 2.8° |
| Center for Clim. Sys. Res (Japan) | MIROC3.2(hires) | 1.125° x 1.125° |
| Met. Res. Inst. (Japan) | MRI | 2.8° x 2.8° |
| NASA Goddard | GISS-AOM | 4° x 3° |
| NASA Goddard | GISS-ER | 5° x 4° |
| Institut Pierre Simon Laplace | IPSL-CM4.0 | 3.75° x 2.5° |

### 3.3 *Influence of Model Resolution*

The UMRB has nominal dimension of $7^o$ N-S by $5^o$ E-W. A comparison of these dimensions with the model resolutions in Table 1 shows that the number of grid points "representing" the basin for the low-resolution models ranges from about 2 for the NASA model to 7 for the GFDL model, and that the high-resolution MIROC model has about 27. By contrast, 111 weather stations were used to represent baseline climate in the region (corresponding to a grid spacing of about $0.6^o$ x $0.6^o$, if they were uniformly distributed).

Ideally, a simulation with SWAT would have at least one weather station per sub-basin. While this condition is met approximately for the observing network in the UMRB and for the grid spacing of regional climate model use by Jha et al. (2004), it is instructive to evaluate the impact of resolution on hydrological components when coarse-resolution model data are used.

We would expect evapotranspiration (ET) and potential evapotranspiration (PET) to be biased low when low-resolution weather data are supplied to SWAT (assuming no changes due to orographic influences and the model does not have a high temperature bias). The Clausius-Clapeyron equation is an exponential function of temperature, so high temperatures proportionately lead to more evaporation/transpiration than low temperatures compared to a linear dependence. Low-resolution models do not capture temperature extremes (either high and low) as well as high-resolution models, and missing extreme high temperatures has a much larger impact than missing extreme low temperatures, especially in summer.

### 3.4 *Influence of Model Biases*

It is noteworthy that precipitation, snowfall, and runoff are "events" whereas snowmelt, baseflow, ET, PET, and total water yield are continuous values. Snowfall (partitioning of precipitation to snow fraction) depends on temperature on the day of snowfall. ET and PET depend on temperature every day (more strongly in the warm season). Other components are not directly (although they are indirectly) dependent on temperature.

A cool bias in the cold season of a GCM model will lead to excessive snowfall (assuming total precipitation is accurately simulated). A comparable warm bias would result in too little snow, of a more-or-less of comparable amount. A cool bias also will lead to reduced ET and PET, particularly if the bias is in the warm season. A comparable warm bias would produce excessive ET and PET of an amount exceeding the reduced values for a cool bias as previously discussed. Since the basin has no permanent snow, annual snowmelt tracks annual snowfall and is unaffected by temperature bias. Likewise, runoff is unaffected by temperature bias. Baseflow and total water yield are not directly affected by temperature but are affected indirectly. High bias on temperature will elevate ET and PET and consequently reduce baseflow, without impact on runoff, thereby reducing total water yield. Likewise low bias on temperature will increase water yield (other factors being equal, of course).

Climate models generally (both global and regional) produce too many light rain events and too few intense events (Gutowski et al., 2003) even if rainfall totals are accurate. The impact of this bias, compared to the true intensity spectrum, is to reduce runoff and increase ET and/or baseflow. Low bias on rainfall likely would lead to low runoff, baseflow, ET, and hence water yield, while excess rain would have the opposite effect. Biases in wind speed, solar radiation, and humidity would likely have less prominent effects in this basin.

## 4. RESULTS

### 4.1 *Biases*

Rainfall gauges from the 111 locations in the UMRB provide measurements of precipitation, and gauge data from Grafton, IL provide measurements of streamflow. However, since no other hydrologic components are measured, we estimate these with SWAT-derived hydrologic components created with weather station input (OBS/SWAT).

Comparison of calculations of streamflow by SWAT using observed weather input with gauge data revealed that SWAT introduces a slight positive bias to annual streamflow but represents the interannual variability quite well (Takle et al., 2005). Biases generated by the combination of GCM and SWAT (Table 2) were calculated by comparing GCM/SWAT results for the 1961-2000 period with OBS/SWAT results.

The GCMs underestimate annual precipitation in the region on average, by a modest amount, but overestimate streamflow. Most models produce too much snow but are quite inconsistent regarding the amount of runoff produced. Baseflow is uniformly high compared to SWAT results produced by station-derived weather, but PET and ET are uniformly low. Total water yield is overestimated by all but one model.

The discussion presented in the previous section provides insight for interpreting these results. The components for which the models produce the most consistent results are ET and PET, which are quite uniformly underestimated (by 25% and 38%, respectively). Although this could signal a uniform positive temperature bias in the warm season, we suggest the more likely cause is coarse resolution of the models (see previous section). It is noteworthy that the only high-resolution model of the ensemble (MIROC3.2-hires) has the lowest bias of all models for both ET and PET. The deficiency in ET forces a model to partition more soil water input to baseflow, which is a likely explanation for uniformly excessive baseflow across the ensemble. And because baseflow is the dominant contributor to total water yield, which also is over-predicted by all but two models, we can say with some confidence that streamflow is over-predicted in this basin by global models because of failure to resolve daily maximum temperatures in summer due to coarse resolution.

### 4.2 *Climate Change*

Although there is inconsistency among models, the mean precipitation created by the ensemble suggests an increase of 6% due to climate change. ET and PET calculations give positive changes for all models, with more uniformity in ET. These changes likely result from higher temperatures in the warm season of future climates. Substantial decreases in snowfall suggest that future scenario winters are warmer as well. Runoff decreases substantially for most models, possibly due to enhanced drying of soils (due to enhanced ET) between rains, which then can hold more precipitation when the next event occurs. Total water yield varies widely among models, with the ensemble mean giving almost no change from the contemporary climate.

## 5. CONCLUSIONS

Ensemble mean results showed only modest changes in precipitation and streamflow for the UMRB for the end of the 21st century (increases of 6% and 3%, respectively). Snowfall is substantially reduced over the basin in the future scenario climate (down 37%). Low resolution of global model results contributes to low biases in ET and PET, which, in turn, give high biases for baseflow. Despite these biases an increase in baseflow of 12% and decrease of runoff of 20% are simulated for the future scenario.

ACKNOWLEDGEMENT. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

## REFERENCES

Arnold, J.G., and N. Fohrer. 2005. Current capabilities and research opportunities in applied watershed modeling. *Hydrolog. Processes, 19*, 563-572.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001 - The scientific basis*, J.T. Houghton, T.Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, and D. Xiaosu (Eds.), 944pp., Cambridge Univ. Press, Cambridge.

Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V. N. Razuvaev. 2005. Trends in intense precipitation in the climate record. *J. Climate*, **18**, 1326-1350.

Gutowski, W. J. Jr., S. G. Decker, R. A. Donavon, Z. Pan, R. W. Arritt, and E. S. Takle. 2003. Temporal-spatial scale of precipitation errors in central US climate simulation. *J. Climate*, **16,** 3841-3847.

Jha, M., Z. Pan, E. S. Takle, R. Gu. 2004. Impact of climate change on stream flow in the Upper Mississippi River Basin: A regional climate model perspective, *J. Geophys. Res., 109*, D09105, doi:10.1029/2003JD003686.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan, and J.R. Williams. 2002. Soil and Water Assessment Tool: User Manual, Version 2000. Texas Water Resour. Inst. TR-192. GSWRL 02-02, BRC 02-06. 455 pages.

Program for Climate Model Diagnosis and Intercomparison (PCMDI). 2005. http://www-pcmdi.llnl.gov/

Stocker, T. F., and C. C. Raible. 2005. Water cycle shifts gear, *Nature, 434*, 830-833.

Takle, E. S., M. Jha, and C. J. Anderson. 2005. Hydrological cycle in the Upper Mississippi River Basin: 20th century simulations by multiple GCMs. *Geophys. Res. Lett.,* 32, L18407 10.1029/2005GL023630

US Department of Agriculture (USDA) Soil Conservation Service. 1972. *National Engineering Handbook*, Section 4 Hydrology, chapters 4-10.

Wu, P., R. Wood, and P. Stott. 2005. Human influence on increasing Arctic river discharges, *Geophys. Res. Lett., 32*, L02703, doi:10.1029/2004GL021570.