Climate Change Impacts on the Hydrology and Water Quality of the Upper Mississippi River Basin

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INTRODUCTION

MOTIVATION

Recent observations and modeling suggest acceleration of the hydrological cycle at high latitudes in the Northern Hemisphere (Stocker and Raible, 2005; Wu et al., 2005). Detailed evaluation of the spectrum of precipitation events for the central US (Groisman, et al, 2005) reveals that the occurrence of extreme intense precipitation events has increased over the twentieth century. Most notably, however, all of this increase (20% increase, statistically significant at the 0.01 level) occurred during the last 30 years of the twentieth century. Assessments of local and regional impacts of changes in the hydrological cycle in future climates call for improved capabilities for modeling the hydrological cycle and its individual components at the subwatershed level.

We report a small step toward resolving the question of optimal strategy for downscaling results of global climate models to estimate annual streamflow. We use 20th century (20C) results of nine global climate models being made available for IPCC 4th Assessment Report [*PCMDI*, 2005] directly as input to SWAT to examine the resulting uncertainty in regional hydrological components.

MODELING STRATEGY

MODELS

SWAT (Arnold and Fohrer, 2005) is a continuous time, long-term, watershed-scale hydrology and water quality model. Meteorological input to SWAT includes daily values of maximum and minimum temperature, total precipitation, mean wind speed, total solar radiation, and mean relative humidity.

Global model results were available from nine models (see Table 1) in the IPCC Data Archive [*PCMDI*, 2005], including two versions of models from three of the laboratories. While not spanning the full range of model variability and giving disproportionate weight to models from these three laboratories, results derived therefrom give a preliminary view of streamflow resulting from direct use of data generated by multiple GCMs. We use model output from the runs simulating the 20C (1961-2000).

Table 1. Global models used in the SWAT-UMRB simulations.

Institution	Model Name	Lon x Lat Resolution	W/m2 Cl. Sens
NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM 2.0	2.5° x 2.0°	2.9
NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM 2.1	2.5° x 2.0°	2.0
Center for Climate System Research (Japan)	MIROC3.2(medres)	2.8° x 2.8°	1.3
Center for Climate System Research (Japan)	MIROC3.2(hires)	1.125° x 1.125°	1.4
Meteorological Research Institute (Japan)	MRI	2.8° x 2.8°	0.86
NASA Goddard Institute for Space Studies (USA)	GISS-AOM	4° x 3°	2.6
NASA Goddard Institute for Space Studies (USA)	GISS-ER	5° x 4°	2.7
Institut Pierre Simon Laplace (France)	IPSL-CM4.0	3.75° x 2.5°	1.25
Canadian Centre for Climate Modeling & Analysis Canada)	CGCM3.1(T47)	3.8° x 3.8°	n/a

Figure 1. The Upper Mississippi River Basin (UMRB) and delineated subwatersheds.

DOMAIN

The UMRB has a drainage area of 447,500 km² up to the point just before the confluence of the Missouri and Mississippi Rivers (Grafton, IL) (Figure 1). Land cover in the basin is diverse and includes agricultural lands, forests, wetlands, lakes, prairies, and urban areas.

For modeling with SWAT, the basin is divided into 119 subwatersheds, each of which is subdivided in hydrological response units (HRUs) such that the basin consists of 474 HRUs. Observed climate data used as input to the hydrological model are provided by 111 weather stations distributed relatively uniformly across the basin. Details of land use, soils, and topography data for the UMRB are provided in *Jha et al*. [2004].

RESULTS

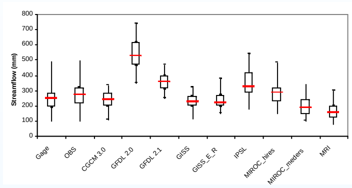

Figure 2. Variability of annual values of GCM/SWAT simulations for a sub-period of the 20C. Measured data at Grafton, IL are labeled as Gage, and SWAT run driven by observed climate is labeled as OBS. Plotted values give median (bold line), quartiles (box values), and lowest and highest values (extremes of whiskers). Dotted line gives mean of the data reported by the gage at Grafton, IL.

Table 2. P-values of T-test of individual GCM/SWAT streamflow and pooled GCM/SWAT streamflow (labeled as GCM POOL) compared to OBS/SWAT.

GCMs	P-value
GFDL-CM 2.0	4.8303E-17
GFDL-CM 2.1	3.3774E-5
MIROC3.2(medres)	4.1050E-5
MIROC3.2(hires)	0.8312
MRI	0.3963E-8
GISS-AOM	0.0098
GISS-ER	0.0124
IPSL-CM4.0	0.0050
CGCM3.1(T47)	0.0229
GCM POOL	0.5979

Table 3. Hydrological components simulated by SWAT.

Hydrological components	OBS (1968-1997)	Measured Data	HadCM2/ RegCM2 ~1990	GFDL-CM 2.0	GFDL-CM 2.1	MIROC 3.2 (medres)	MIROC 3.2 (hires)	MRI	GISS-AOM	GISS-ER	IPSL-CM 4.0	CGCM 3.0
Precipitation	846	846	900	1032	910	736	821	707	746	746	793	859
Snowfall	118	-	244	213	196	110	104	134	125	95	202	140
Snowmelt	116	-	241	211	193	107	100	130	120	94	200	138
Surface runoff	100	-	148	215	140	55	75	58	63	51	147	80
Baseflow	181	-	213	330	223	145	213	109	170	182	196	161
Potential ET	967	-	788	759	854	1054	984	1011	744	729	692	970
Evapotranspiration (ET)	557	-	533	484	540	531	527	532	505	506	445	611
Total water yield	275	253	350	531	353	194	279	162	227	227	336	232

Notes: 1. Measured streamflow data is at Grafton, IL (USGS gage # 05587450).
2. All values are average annual values (in mm) averaged over 1963-2000 (unless otherwise specified); Years 1961 and 1962 are simulated as initialization period.
3. HadCM2/RegCM2 SWAT simulations are average over 10-year period.

Table 4. Results for the ensemble mean of SWAT driven by GCMs and observed meteorological conditions for the 20C.

Hydrological components	OBS/ SWAT	Measured data	GCM/SWAT		MIROC 3.2 (hires)		HadCM2/RegCM2 /SWAT	
			Mean	% diff.	Amount	% diff.	Amount	% Diff.
Precipitation	846	846	817	-03	821	-03	900	+ 06
Snowfall	118	-	147	+25	104	-12	244	+206
Snowmelt	116	-	144	+24	100	-13	241	+208
Surface runoff	100	-	98	-02	75	-25	148	+ 48
Baseflow	181	-	192	+06	213	+18	213	+ 18
Potential ET	967	-	866	-10	984	+02	788	- 15
ET	557	-	520	-07	527	-05	533	- 04
Total water yield	275	253	282	+11	279	+10	350	+ 38

Note: Percent differences are calculated from measured data when available and otherwise from results of SWAT driven by observed meteorology. The datasets used different averaging periods as follows: OBS/SWAT: 1968-1997; GCM/SWAT: 1963-2000; MIROC3.2 (hires)/SWAT: 1963-2000; and HadCM2/RegCM2/SWAT: 1990-1999.

SWAT calculates components of the hydrological budget from the meteorological data supplied by each model. Rainfall gauges from the 111 locations in the UMRB provide measurements of precipitation, and gauge data at Grafton provide measurements of streamflow. However, since no other hydrological components are measured, we estimate these with SWAT-derived hydrological components created with weather-station input. GCM/SWAT ensemble means of hydrological components show quite good agreement with gauge data and observations-driven simulations (Table 4). Snowfall (and resulting snowmelt) presents the dominant challenge among the hydrological components. The high-resolution MIROC3.2 results agree with observations.

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CONCLUSIONS

We previously reported results of using a regional climate model (RegCM2) to dynamically downscale results of a global model (HadCM2) to the UMRB [*Jha et al.*, 2004]. The HadCM2/RegCM2/SWAT results (Table 4) show large differences from the GCMs in partitioning precipitation to snowfall (27%), which can be traced to a 1-2 mm/day positive bias in precipitation by HadCM2/RegCM2 in winter and spring.
From Tables 3 and 4, we conclude that: (1) use of a GCM drawn at random to drive SWAT could lead to sizable errors in streamflow and hydrological cycle components, (2) use of the mean streamflow from an ensemble of GCM/SWAT simulations, by contrast, performs quite well for this task, (3) the lone high-resolution GCM does as well as the ensemble mean despite large errors in its lower-resolution sister model, and (4) the downscaled results of a global model by a regional model (models chosen on the basis of availability) used to drive SWAT are inferior to those resulting from the GCM model mean and the high-resolution GCM.

Table 2. Model biases and climate change for each hydrological cycle component.

Hydrologic Component/ Model	Bias(%)	Change (%)	Hydrologic Component/ Model	Bias(%)	Change (%)
Precipitation			Snowfall		
GFDL 2.0	22	1	GFDL 2.0	81	-32
GISS AOM	-12	17	GISS AOM	6	-22
GISS ER	-12	25	GISS ER	-19	3
IPSL	-6	0	IPSL	71	-43
MIROC-hi	-3	-4	MIROC-hi	-12	-80
MIROC-med	-13	-12	MIROC-med	-7	-65
MRI	-16	16	MRI	13	-18
Mean	-6	6	Mean	19	-37
Snowmelt			Runoff		
GFDL 2.0	83	-32	GFDL 2.0	155	-30
GISS AOM	5	-20	GISS AOM	-24	-2
GISS ER	-19	5	GISS ER	-39	32
IPSL	73	-43	IPSL	73	-31
MIROC-hi	-12	-79	MIROC-hi	-9	-38
MIROC-med	-6	-65	MIROC-med	-30	-63
MRI	13	-17	MRI	-21	-7
Mean	20	-36	Mean	15	-20
Baseflow			Potential ET		
GFDL 2.0	176	4	GFDL 2.0	-54	45
GISS AOM	50	43	GISS AOM	-42	5
GISS ER	76	45	GISS ER	-49	5
IPSL	22	-5	IPSL	-34	46
MIROC-hi	63	-12	MIROC-hi	-24	37
MIROC-med	27	-32	MIROC-med	-29	32
MRI	11	38	MRI	-34	14
Mean	61	12	Mean	-38	27
ET			Total Water		
GFDL 2.0	-37	16	GFDL 2.0	154	-8
GISS AOM	-26	7	GISS AOM	16	33
GISS ER	-30	12	GISS ER	27	43
IPSL	-25	12	IPSL	33	-17
MIROC-hi	-18	6	MIROC-hi	29	-18
MIROC-med	-20	3	MIROC-med	0	-40

BIASES

The GCMs generally underestimate annual precipitation 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.

Models produce the most consistent results for ET and PET, which are quite uniformly underestimated (by 25% and 38%, respectively). 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 likely explains the uniformly excessive baseflow across the ensemble. And because baseflow is the dominant contributor to total water yield, which also is over-predicted in 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.

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 temperature increases in the warm season. Substantial decreases in snowfall suggest that warming is strong in winter as well. Runoff decreases substantially for most models, possibly due to enhanced drying of soils (due to enhance ET) between rains, which then can hold more precipitation during the next event. Total water yield shows wide variance among the models, with the ensemble mean showing almost no change from the contemporary climate.

IMPACT ON WATER QUALITY

Fugitive sediment from the landscape is carried by overland flow (runoff), but the dominant pathway for nitrate loss is through leaching to groundwater and then via baseflow or tile drains (Randall, 2001). Results show a substantial decrease in runoff in the future climate but increase in baseflow, although with less agreement among models. We speculate that both sediment and nitrate loading of streams would decrease due to decreased runoff but that nitrate leaching might increase. Therefore, although water quality might improve due to reduced sediment, the loading due to nitrates is less clear but might increase.

CONCLUSIONS

Output from an ensemble of nine GCMs was used to drive SWAT. We found that streamflow data resulting from the GCMs are serially uncorrelated at all lags and form 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. The ensemble mean of GCM/SWAT simulations demonstrated good performance in reproducing observed precipitation (3% error) and streamflow (11% error) despite large differences among ensemble members.
Evaluation of the impact of resolution with two runs of the same GCM calls for further study of the benefits of grid refinement.
Statistical tests indicated that, of all models used, only the MIROC3.2(hires) – the only high resolution model tested - correctly simulates observed streamflow.

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.
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.
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.