Water yield responses to high and low spatial resolution climate change scenarios in the Missouri River Basin

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[1] Water yield responses to two climate change scenarios of different spatial scales were compared for the Missouri River Basin. A coarse-resolution climate change scenario was created from runs of the Commonwealth Scientific and Industrial Research Organization General Circulation Model (CSIRO GCM). The high-resolution climate change scenario was developed using runs of the Regional Climate Model RegCM, for which the GCM provided the initial and lateral boundary conditions. Water yield responses to the high- and low-resolution climate change scenarios were investigated using the Soil and Water Assessment Tool (SWAT). Basin-wide water yield increased for both GCM and RegCM scenarios but with an overall greater increase for the RegCM scenario. Significant differences in water yields were found between the GCM and RegCM climate scenarios. *INDEX TERMS:* 1630 Global Change: Impact phenomena; 1655 Global Change: Water cycles (1836); 1803 Hydrology: Anthropogenic effects; 1860 Hydrology: Runoff and streamflow. **Citation:** Stone, M. C., R. H. Hotchkiss, and L. O. Mearns, Water yield responses to high and low spatial resolution climate change scenarios in the Missouri River Basin, *Geophys. Res. Lett.*, *30*(4), 1186, doi:10.1029/2002GL016122, 2003.

1. Introduction

[2] Climate change impact studies are often conducted using General Circulation Models (GCMs) to produce climate change scenarios. However, their coarse horizontal resolution (100s of kms) has been problematic for impacts applications, including hydrology, since most impacts are investigated at very local to regional scales [*Hostetler*, 1994]. Several techniques exist for generating high-resolution climate change scenarios [*Giorgi et al.*, 1998; *Mearns et al.*, 1999a; *Wilby and Wigley*, 1997]. However, little research has been performed to indicate whether the higher resolution scenarios result in important differences in the calculation of climate change impacts. *Mearns et al.* [1999b, 2001] recently established that the spatial resolution of climate change scenarios can affect the determination of the impacts of climate change on simulated crop yields and agricultural economic assessments, and that spatial scale should be considered a critical uncertainty in climate change impacts assessments. *Wilby et al.* [2000] found a greater reduction in runoff from a GCM climate change scenario when compared to that from a regional climate model scenario in the Animas River Basin in Colorado. However, differences in water yields calculated from GCM and regional climate model scenarios have not been compared for a major river basin.

[3] The uncertainty in hydrologic impacts due to the spatial scale of climate scenarios needs further exploration. Given the computer and human resources needed to generate higher resolution scenarios, it is important to determine the added value and/or further uncertainty in impacts assessment that result from their use. Moreover, the differences in hydrological impact could have implications for water resource planning in the long-term future.

[4] In this project, two climate change scenarios were developed for the Missouri River Basin: one from a coarse grid GCM and one from a fine scale Regional Climate Model (RCM). The GCM provided the initial and lateral boundary conditions for driving the RCM. Impacts of these scenarios on water yields were analyzed using the Soil and Water Assessment Tool (SWAT) hydrologic model.

2. Methods

[5] The Commonwealth Scientific and Industrial Research Organization (CSIRO) GCM was used for this study. The CSIRO GCM was run to simulate control and equilibrium doubled CO_2 climate conditions at a spatial resolution of about 400 km by 500 km. The simulations with the CSIRO GCM are described in detail by *Watterson et al.* [1997] and *Watterson* [1998] and *Giorgi et al.* [1998]. These simulations were chosen for this study because the control run was reasonably accurate in reproducing the major climate features over the region of interest.

[6] The high-resolution climate change scenario was developed at a 50 km grid point spacing over the western two-thirds of the continental US, using the National Center for Atmospheric Research (NCAR) RegCM2 (henceforth referred to as RegCM) driven by initial and lateral boundary conditions by the control and doubled CO_2 simulations of the GCM [*Giorgi et al.*, 1998]. For most of the Missouri Basin, under climate change, the GCM and RCM both simulate precipitation increases in all seasons, but the increases are larger and/or cover more of the basin in the case of the RegCM. Increases in precipitation for the RegCM are also more spatially variable than those of the GCM. Temperature increases range from about 4 deg. C in the summer to about 8 deg. C in the winter in the northern portions of the basin.

[7] It is not assume that the climate change scenarios used here are preferable to those generated with other climate

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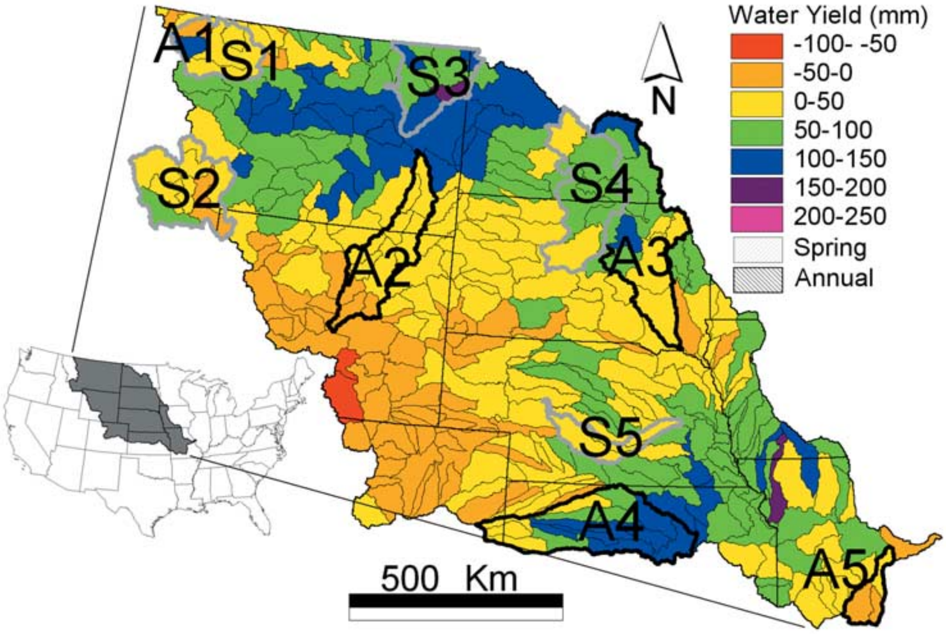

Figure 1. Selected basins for spring (S) and annual (A) statistical comparisons and differences between RegCM and GCM annual water yields.

models. Different GCMs respond differently to the same external forcings. This constitutes one of the important uncertainties in projections of climate change. For example, the two climate models used in the US Assessment had very different responses to the same emission scenarios, particularly regarding precipitation, one exhibiting mainly increases and the other decreases [*Felzer and Heard*, 1999]. The goal is to determine the sensitivity of the impact model to the two scenarios that are physically related but represent the climate change at two different spatial scales.

[8] Climate change scenarios were created using conventional methods to modify observed climate records (1965–1989) obtained from the National Weather Service (NWS) Cooperative Observer Program (COOP). This data set included approximately 2000 gages in the Missouri River Basin. Mean precipitation and temperature values were generated using the Thiessen Polygon method [*Thiessen*, 1911]. The SWAT Weather Generator was used to produce representative daily solar radiation, wind speed, and relative humidity values based on statistical information from NWS data. Temperature change scenarios were created by adding monthly-averaged temperature differences between the baseline and double CO_2 simulations to observed daily climate records. Daily precipitation, relative humidity, solar radiation, and wind speed were adjusted by the ratio of the doubled CO_2 conditions to the control [*Stone et al.*, 2001].

[9] Water yield modeling was completed using SWAT, a continuous watershed scale model that simulates the major components of the hydrologic cycle on a daily time step [*Arnold et al.*, 1998]. SWAT is a watershed-structured program that divides the area modeled into topographically defined watersheds. The Missouri River Basin, with an area of 1.8 million km^2, was divided into 310 subbasins based on USGS-defined 8-digit watersheds. Each watershed was partitioned into as many as 30 additional subbasins based upon land use and soil composition resulting in over 6,000 subbasins with an average area of 300 km^2. Each subbasin within the 8-digit watersheds shares the same weather data file.

[10] Three simulations with SWAT were conducted: (1) a baseline simulation using 25 years (1965–1989) of historic and stochastically completed climate data; (2) a doubled CO_2 simulation using GCM climate change results to modify historic data; and (3) a doubled CO_2 climate change simulation using RegCM climate change results to modify historic data.

3. Results

[11] Hydrologic model results are summarized for the baseline, RegCM, and GCM climate scenarios. Water yields are investigated at multiple spatial and temporal scales.

Table 1. Median Water Yields for Five Basins Baseline and Two Climate Scenarios, First and Third Quartiles in Parentheses

	Median Spring Water Yields (mm)			Median Annual Water Yields (mm)		
Basin	Baseline	GCM	RegCM	Baseline	GCM	RegCM
1	68 (52–94)	104 (88–129)	123 (94–160)	183 (68–110)	202 (155–259)	244 (200–303)
2	27 (17–40)	51 (36–76)	72 (59–123)	32 (19–41)	88 (56–113)	109 (49–133)
3	12 (8–20)	30 (21–43)	47 (37–67)	51 (47–62)	145 (126–177)	208 (184–247)
4	17 (13–23)	38 (25–48)	56 (40–74)	62 (38–77)	123 (81–135)	178 (118–217)
5	63 (47–75)	86 (62–105)	105 (88–152)	523 (458–629)	629 (577–760)	627 (539–787)

Table 2. Basin-Wide, Mean Annual Hydrologic Values for Baseline and Two Climate Scenarios, All in mm

Basin-Scale	Precip	Snow	Runoff	ET	Wyld
A3-Base	626	29	61	535	80
A3-GCM	731	35	126	520	185
A3-RegCM	737	33	135	519	192
A5-Base	1072	19	249	494	548
A5-GCM	1182	22	316	491	652
A5-RegCM	1158	26	320	482	648

Water yield is defined as the net amount of water that leaves the subbasin and contributes to streamflow.

[12] A statistical analysis was completed to compare model water yields for each scenario. Spring and annual water yields were considered for the 25-year simulation. Spring water yields were analyzed because it is a critical season for snowmelt, runoff, and water supply. Interbasin correlations were calculated for all basins using statistical software. Basins with correlations below 0.5 were considered mutually uncorrelated. For each temporal scale (spring and annual), five regions with mutually uncorrelated water yields were selected. The regions were consistent with USGS 6-digit watersheds and are displayed in Figure 1.

[13] Median water yields in the five basins under the three climate scenarios are shown in Table 1. Medians were used because the frequency distributions were substantially skewed. The first and third quartiles (in parentheses) show the interannual variability in water yield. For comparison, mean annual values for the major hydrologic processes (precipitation, snowfall, runoff, evapotranspiration, and water yield) are shown in Table 2 for two of the selected basins. Precipitation and runoff values were higher while evapotranspiration values were lower for both basins under the climate change scenarios.

[14] In both spring and annual data sets, the frequency distribution of water yields differed considerably between the five basins, both in mean and variance. A cube-root transformation (z_i = water yield ^ (1/3)) was applied to the water yield data to assure that the data was normally distributed and that the subgroups had similar variances. This transformation produced approximately normal distributions for all basins and climate cases examined based on the Shapiro-Wilk statistic [*Shapiro and Wilk*, 1965]. Analysis of variance (ANOVA) methods were used to compare the transformed model water yields, z_i. A 2-way analysis of variance model was used, with a basin-by-scenario interaction term that controls for differences between basins in mean z_i.

[15] For both spring and annual water yields, the scenario effect and the basin-by-scenario interaction were statistically significant (using a 99% confidence level). Pairwise comparisons show that model water yields are significantly different in all three pairings of baseline and the two climate scenarios. That is, water yields are significantly greater in both climate change scenarios than in the present climate (base scenario). Also, water yields predicted by the RegCM were significantly greater than those predicted by the GCM.

[16] The significant basin-by-climate interaction indicates that the effect of climate scenario differs between basins. Average annual water yield differences between RegCM and GCM scenarios (RegCM minus GCM) averaged for the 25-year simulations are displayed in Figure 1 at the 8-digit subbain scale. Although RegCM yields were generally higher than GCM yields, differences ranged from −100 mm to 250 mm. The same pattern was observed for annual water yields at a yearly time scale. For example, annual water yields for two 6-digit basins are shown in Figures 2 and 3. Annual yields were clearly lower under the base scenario than under the two climate change scenarios. The basins differ though in comparison of RegCM and GCM yields. In basin 3, RegCM water yields were substantially greater than GCM yields. However, yields from the two climate change scenarios were quite similar in basin 5. This variation in response can be attributed to the smaller contrast in precipitation changes in the southern portion of the Missouri River basin.

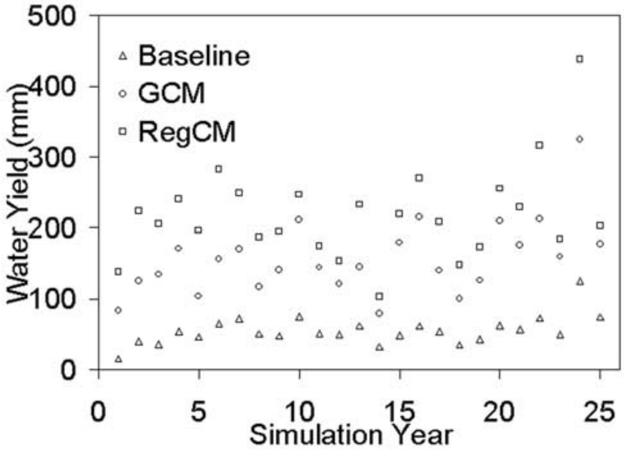

Figure 2. Annual water yields for basin 3 for baseline, GCM, and RegCM scenarios.

[17] Differences between RegCM and GCM water yields were also investigated on a monthly time scale. Monthly variations in water yield differences for all 8-digit subbasins for the 25-year simulation are displayed in Figure 4. The shaded bars represent water yield differences between the 10th and 90th percentiles and the line bars display minimum and maximum values. Most water yield differences were within ±10 mm but maximum differences exceeded 90 mm.

[18] Causes for the contrasts in water yield between the scenarios on all time scales may be traced to the larger

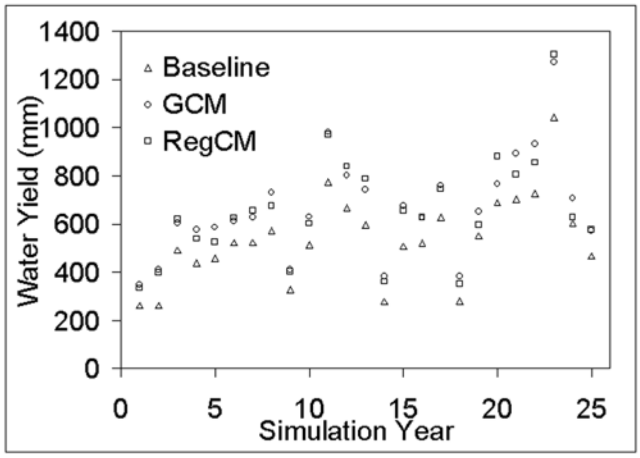

Figure 3. Annual water yields for basin 5 for baseline, GCM, and RegCM scenarios.

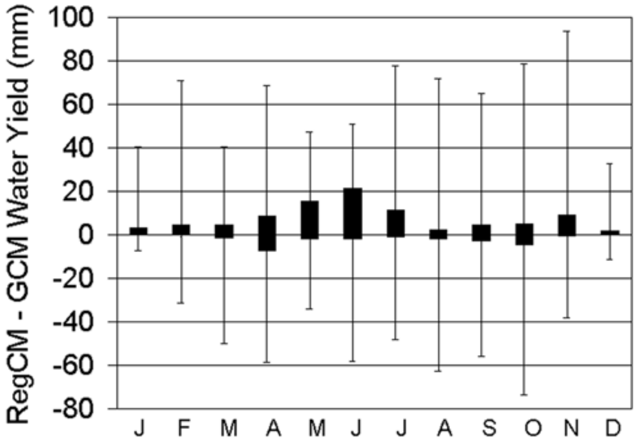

Figure 4. Variation in monthly water yields for 8-digit basins.

increases in precipitation in all seasons for the RegCM scenario, as well as the larger temperature increases in the GCM. Increased temperature results in increased potential evapotranspiration and altered plant biomass production.

[19] The above results suggest that spatially complex climate change patterns produced by high-resolution models have a significant impact on water yield predictions. This can be attributed to the non-linear nature of many processes within the hydrologic cycle. For example, increases in precipitation are magnified through the infiltration process, modeled in SWAT using the SCS Curve Number Procedure [*Mockus*, 1972]

$$Q = \frac{(P - 0.2\,S)}{P + 0.8\,S} \tag{1}$$

where P and Q equal daily precipitation and runoff respectively (mm), and S is the soil moisture retention (mm). In Equation 1, runoff approaches precipitation non-linearly. The non-linear characteristics of the Curve Number Procedure are indicative of many processes in the hydrologic cycle. Climate change also has a non-linear affect on agricultural-based processes such as biomass production, soil moisture content, and evapotranspiration, which all impact water yield.

4. Conclusion

[20] These findings indicate that the use of high-resolution climate change scenarios for regional impact studies significantly affects estimations of changes in water yield under climate change conditions, when compared with results from coarse resolution GCMs. While it cannot be concluded decisively that confidence is increased for the impacts results from the high-resolution scenario, improvements in the reproduction of the current climatology of regions using regional models indicate that their responses to future forcing of the climate may be more robust than those of coarse resolution models. Further research is needed to place the uncertainty of spatial scale of scenarios in the context of other uncertainties of future climate, such as uncertainty of global climate model response and uncertainty in future emissions of greenhouse gases.

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