CLIMATE CHANGE IMPACTS FOR THE CONTERMINOUS USA: AN INTEGRATED ASSESSMENT

PART 4: WATER RESOURCES

ALLISON M. THOMSON[1], ROBERT A. BROWN[2], NORMAN J. ROSENBERG[1], RAGHAVAN SRINIVASAN[3] and R. CESAR IZAURRALDE[1]

[1]*Joint Global Change Research Institute, 8400 Baltimore Ave., Suite 201, College Park, Maryland 20740, U.S.A.*
E-mail: Allison.Thomson@pnl.gov
[2]*Independent Project Analysis, 11150 Sunset Hills Road, Suite 300, Reston, Virginia 20190, U.S.A.*
[3]*Blackland Research Center, 720 E. Blackland Road, Temple, Texas 76502, U.S.A.*

Abstract. Global climate change will impact the hydrologic cycle by increasing the capacity of the atmosphere to hold moisture. Anticipated impacts are generally increased evaporation at low latitudes and increased precipitation at middle and high latitudes. General Circulation Models (GCMs) used to simulate climate disagree on whether the U.S. as a whole and its constituent regions will receive more or less precipitation as global warming occurs. The impacts on specific regions will depend on changes in weather patterns and are certain to be complex. Here we apply the suite of 12 potential climate change scenarios, previously described in Part 1, to the Hydrologic Unit Model of the United States (HUMUS) to simulate water supply in the conterminous United States in reference to a baseline scenario. We examine the sufficiency of this water supply to meet changing demands of irrigated agriculture. The changes in water supply driven by changes in climate will likely be most consequential in the semi-arid western parts of the country where water yield is currently scarce and the resource is intensively managed. Changes of greater than ±50% with respect to present day water yield are projected in parts of the Midwest and Southwest U.S. Interannual variability in the water supply is likely to increase where conditions become drier and to decrease under wetter conditions.

1. Introduction

Global warming from increases in atmospheric greenhouse gasses will alter weather patterns around the globe and affect the hydrologic cycle and freshwater supplies. The capacity of the atmosphere to hold water will increase, leading to more precipitation and evaporation globally. However, not all regions of the world will experience an increase in precipitation; some regions will experience a drying. In many regions of the world, water is in short supply under current climatic conditions, and accurate predictions of future water supplies are critical to water resources management decisions and adaptation strategies (Alcamo et al., 2000). Public awareness is growing in the United States that water is a finite resource and, as a result, freshwater withdrawals have declined over the last two decades even as population has

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increased (Solley et al., 1998). However, during the same time period, irrigation, the largest consumptive use of water, has increased. But as populations continue to increase, and with water supplies uncertain as climate changes, agriculture may come under increasing pressure to relinquish its claims to water. Future water resources planning may be further complicated by changes in climate, which may alter key components of the water cycle (e.g., precipitation and evapotranspiration). Studies of the effects of climate change on water resources are needed to define the potential magnitude of these changes.

The recent U.S. National Assessment of Climate Change (NACC) notes that global average precipitation will increase but the regional impacts are unknown and difficult to predict (Gleick et al., 2000). One complicating factor in assessing the potential impacts of climate change is that General Circulation Models (GCMs) do not agree on regional changes in precipitation or temperature (Lettenmaier et al., 1999; Kirshen and Fennessey, 1995; Wolock and Hornberger, 1991; Wolock and McCabe, 1999). Therefore, it is important to understand how water supplies might change in any given region under a range of climate change scenarios.

In addition to changes in temperature and precipitation, changes in vegetation can also affect water resources. Plant cover and physiology will change with rising atmospheric carbon dioxide concentration ($[CO_2]$) and interactions between water resources and vegetation will be altered. Increased precipitation enhances vegetative growth in arid regions and higher temperatures lengthen the frost-free growing season. These effects could increase leaf area index (LAI) and plant cover (Allen et al., 1991). Greater plant cover would increase the amount of water consumed by plants, reducing runoff while increasing overall evapotranspiration (ET). Conversely, the increase in atmospheric CO_2 is expected to influence plant physiology by increasing stomatal resistance and decreasing water lost through ET (Wolock and Hornberger, 1991; Allen et al., 1991). These contradictory effects were noted by Lettenmaier et al. (1999) and Brown and Rosenberg (1997) who found that the increase in ET with higher temperatures compounded the increasing dryness in regions receiving less precipitation and moderated runoff increases in regions where increased precipitation was predicted.

Water is a heavily managed natural resource in arid regions where there are many competing demands for it including municipal uses, industrial production, recreation, wildlife habitat, hydropower and agriculture. Much of the increase in global agricultural production over the past 50 yr is due to increased area of irrigated crops in arid regions. Significant reductions in water supply would make irrigation more difficult or impossible in certain regions, while increases in rainfall could allow marginal lands to support agricultural production, shifts to higher value crops to occur and/or reductions in actual demands for irrigation water. Increases in precipitation and water yield could also have negative consequences for agriculture if they come in the form of damaging storms that erode soils and flood the land, although we do not consider that case in this study.

A study of the sort reported here can provide useful information for overall national water policy. Gleick (1990) developed an index of regional water vulnerability or resilience based on five criteria descriptive of hydrologic basins: (1) ratio of storage to total annual mean renewable supply; (2) ratio of basin consumptive depletions to total annual mean renewable supply; (3) ratio of hydroelectricity to total electricity production; (4) ratio of total annual groundwater overdraft to total groundwater withdrawals; (5) ratio of very high to very low streamflow (variability). Numerical limits are defined for each of these criteria. Under current climate safe limits are exceeded in all five criteria in one of the Major Water Resource Regions (MWRRs) of the conterminous U.S.—the Great Basin. Four safe limits are exceeded in the Missouri and California. Three are exceeded in the Lower Colorado, the Arkansas-White-Red and the Texas-Gulf. The HUMUS simulations presented in this paper show profound changes under at least a few scenarios in most of the 18 MWRRs modeled, it is most interesting to observe the changes that are projected for the most vulnerable basins.

Others have simulated the response of surface water resources to climate change by estimating global river discharge (Miller and Russell, 1992), assessing the impacts on water distribution in individual watersheds (e.g., Boston water supply, Columbia River) (Kirshen and Fennessey, 1995; Wolock and Hornberger, 1991) or multiple watersheds (e.g., Rosenberg et al., 1999 for the Missouri and Arkansas river basins that overlie the Ogallala aquifer). In this study, we examine water resources at the scale of the 2,101 USGS 8-digit hydrologic unit areas within the conterminous United States. We explicitly model the effects of increases in atmospheric CO_2 through the so-called 'CO_2-fertilization effect' in addition to GCM-projected changes in temperature and precipitation—all encompassed in a suite of 12 climate change scenarios. Our purpose is to identify regional changes in annual freshwater supply that might occur and how the seasonal distribution of water supplies might change. Descriptions of the climate change scenarios and the models used in this study can be found in Part 1 of this series. In the paper that follows (Part 5), we use the results of these water resources simulations in combination with the simulations of agricultural production reported in Part 3 to determine whether future water supplies will be sufficient to meet irrigation demands of a future U.S. agriculture. Then in Part 6, we examine natural ecosystem response to the changing climate and water resource regime.

2. Methods

2.1. HYDROLOGIC UNIT MODEL OF THE UNITED STATES (HUMUS)

HUMUS is a GIS-based tool (Arnold et al., 1999; Srinivasan et al., 1993) which provides the input data required to drive the Soil and Water Assessment Tool (SWAT) hydrology model of Arnold et al. (1998). HUMUS can be applied to a wide range of basin sizes depending on the availability of input data and the study objectives.

In this study, we simulate the hydrologic cycle at the scale of the 8-digit USGS hydrologic unit areas (HUA) (USGS, 1987). Input data sets, including weather data (daily maximum and minimum temperature, precipitation, solar radiation and humidity) soil profiles, vegetation cover and land management, were assembled for the conterminous United States at the scale of 1:250,000 and integrated into the HUMUS geographic information system database. These data are passed to SWAT, which represents the basin water balance on a daily time step through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m). The variable in SWAT most comparable to streamflow is water yield, calculated as the sum of runoff, lateral flow from the soil profile, and groundwater flow from the shallow aquifer. For a complete description and validation of HUMUS/SWAT, see Part 2 of this series.

2.2. CLIMATE CHANGE SCENARIOS

The impacts of 12 climate change scenarios on U.S. hydrology were modeled with HUMUS. As explained in Part 1, we captured the range of potential future conditions with three General Circulation Models (GCMs): the Australian Bureau of Meteorology Research Centre (BMRC), the University of Illinois at Urbana Champagne (UIUC) and the UIUC with characterization of atmospheric sulfates (UIUC + Sulfate). Climate change was modeled with each of these at two levels of global mean temperature increase (GMT = +1 or +2.5 °C), and the scenarios were scaled to 0.5° grid cells and applied to the baseline weather stations. To account for the potential impact of 'CO_2-fertilization' on the hydrologic balance, the HUMUS simulations for this study were made under two CO_2 concentrations: present day (365 ppmv) and double the pre-industrial concentration (560 ppmv). Each simulation was run for a 30-yr period under the changed climate conditions (Part 1, Table I). For further information on the GCMs and their climate predictions, see Part 1.

2.3. WATER YIELD VARIABILITY

The coefficient of variation (CV) of annual water yield was calculated for each of the 2,101 8-digit basins over the 30-yr simulation period. CV is defined by (standard deviation)/(mean) × 100. To provide the scenarios of climate change used to drive the HUMUS model (see Part 1), monthly means of maximum and minimum temperature and precipitation derived from the historical daily weather record were adjusted by the average monthly climate changes predicted by the GCMs. Therefore, changes in climate variability are not captured by these scenarios and any changes in the variability of water yield are due to the response of the HUMUS model to the new precipitation and temperature regimes and the effect of these on the basin's vegetation.

TABLE I
Water yield at baseline and change from baseline for the 18 Major Water Resource Regions (MWRRs) under 12 scenarios of climate change

GCM	Baseline	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate
GMT (°C)	0		1.0			1.0			2.5			2.5	
CO_2 (ppmv)	365		365			560			365			560	
MWRR	mm	Change from baseline (mm)											
New Eng.	635	−14	18	21	5	36	39	−41	42	49	−21	62	69
Mid-Atl.	507	−25	15	16	−14	26	27	−62	37	37	−51	47	47
S. Atl-Gulf	605	−36	11	13	−17	30	32	−91	26	30	−73	45	49
G. Lakes	399	−16	13	8	−2	27	22	−39	31	21	−25	46	35
Ohio	550	−29	19	16	−18	35	27	−73	56	37	−61	56	47
Tenn.	779	−40	27	23	−24	41	40	−106	75	51	−90	75	67
U. Miss.	331	−24	21	2	−12	34	13	−57	65	18	−44	65	29
L. Miss.	614	−56	21	10	−28	49	36	−139	84	34	−112	84	61
Sou-R-Rai.	87	−8	7	3	0	15	10	−23	23	6	−16	23	14
Missouri	107	−16	20	17	−11	26	24	−35	55	48	−31	63	55
Ark-W-R.	235	−31	50	38	−19	65	53	−73	139	116	−62	157	133
TX-Gulf	211	−34	46	29	−19	63	47	−83	123	97	−69	142	115
Rio Gr.	40	−10	15	15	−8	18	18	−21	46	44	−21	51	49
U. Colo.	63	−11	14	26	−9	17	30	−23	47	66	−23	51	72
L. Colo.	52	−14	12	27	−12	14	29	−29	40	63	−29	42	66
Gr. Basin	68	−10	19	46	−10	20	48	−26	57	110	−26	60	114
Pac. NW	521	−26	18	65	−15	32	80	−66	38	102	−66	54	119
Calif.	409	−36	11	49	−31	16	55	−83	32	89	−83	38	95

3. Results and Discussion

3.1. IMPACTS ON ANNUAL WATER SUPPLY

3.1.1. *Water Yield on the National Scale*

Figure 1 illustrates the changes in HUMUS-simulated water yield over the conterminous U.S. in response to climate changes projected by the three GCMs. The effects of higher global mean temperature (GMT) are shown in Figures 1a and 1b. The effects of 'CO_2-fertilization' are shown in Figures 1b and 1c for specific changes in precipitation and temperature projected by the three GCMs (see Part 1, Figures 5 and 6).

Figure 1a shows the response of water yield to a 1 °C increase in GMT. The BMRC model shows a marked drying (−25 to −175 mm) across the country, with the most severe declines in water yield in pockets of the lower Mississippi valley and the Pacific Northwest. A few isolated basins show increases in water yield that do not exceed baseline by more than 50 mm. Under the UIUC scenario, water yield declines in relatively few basins and increases over most of the country. The greatest increase occurs in eastern Texas and Oklahoma. Parts of the Gulf Coast, Upper Midwest and Pacific Northwest experience drying. UIUC +Sulfate shows similar trends but with some exceptions. The Great Lakes and Upper Midwest regions experience drying, while water yield increases markedly (more than 150 mm) in some basins of the Pacific Northwest. The increase in GMT from +1 to +2.5 °C (Figure 1b) amplifies the effects of each GCM, but the regional distributions remain similar. One notable change is observed in the upper Midwest region. The small decline in water yield under UIUC +Sulfates at GMT = +1 °C converts to a moderate increase when GMT = +2.5 °C. Precipitation increases in this region under both scenarios; therefore the switch from decrease to increase in water yield as global mean temperature increases illustrates the potential for non-linear regional impacts of climate change.

Under BMRC, the drying is moderated by CO_2-fertilization in the southeast and northern New England (Figure 1c). CO_2-fertilization makes no significant difference in the arid West. With the high temperatures and low precipitation predicted by BMRC for the West, conditions would become harsher and vegetative cover could be reduced, as the BIOME model shows (see Part 6). In such a case the CO_2-fertilization effect on plants would have little impact on regional hydrology. In contrast, UIUC predicts large increases in precipitation in the West and water yield increases with the CO_2 effect due to suppression of evapotranspiration. Response under UIUC + Sulfate is similar, with greater increases in water yield in the West. Geographic patterns in the Pacific Northwest remain complex but with greater water yields in some basins within the region. CO_2-fertilization under UIUC and UIUC + Sulfates increases water yield substantially in eastern Texas, Oklahoma, and Kansas.

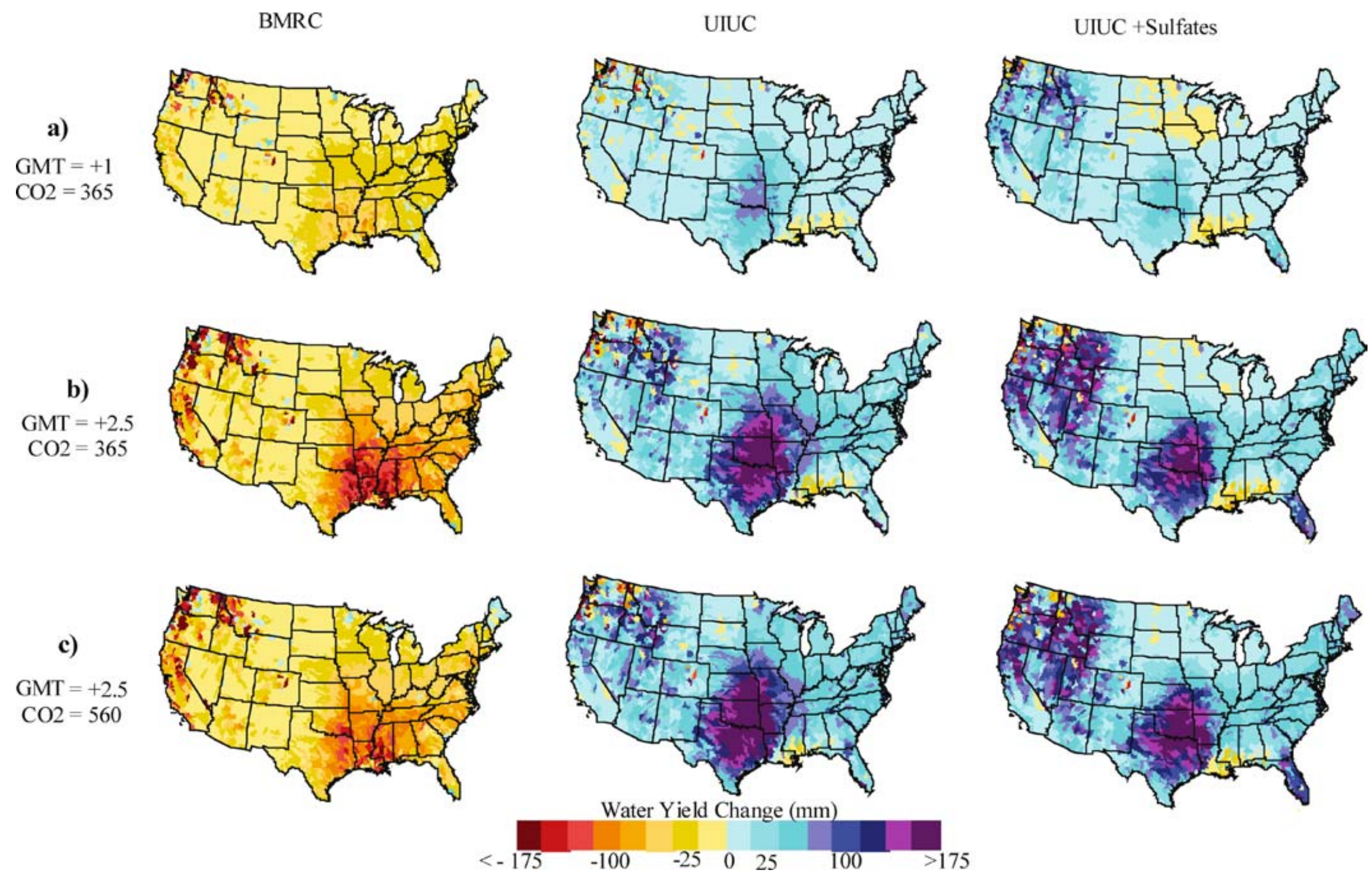

Figure 1. Change in water yield from baseline (mm) for three GCMs with increasing global mean temperature (GMT) with and without the CO_2-fertilization effect.

3.1.2. *Evapotranspiration (ET) on the National Scale*

Changes in ET, reflecting interactions between temperature, precipitation and plant physiology, are shown in Figure 2. In Figure 2a, the response of ET under a 1 °C rise in GMT is consistent with GCM projected changes in temperature and precipitation. BMRC, which projects less precipitation and greater warming than UIUC, decreases ET in the western part of the country where the dryer and hotter conditions limit vegetative cover. BMRC leads to increased ET in the East where higher temperatures increase water use. ET increases under UIUC except in scattered eastern basins as the increased precipitation provides water to plants. UIUC + Sulfate increases ET in portions of the West and moderates decreases throughout the central part of the country. Increases are greatest in the arid western regions where this GCM predicts higher precipitation than does UIUC. An increase in GMT of 2.5 °C (Figure 2b) amplifies the effects discussed above with sharper declines in ET in the West and greater increases in the East and Pacific Northwest.

Atmospheric CO_2 increases stomatal resistance which reduces ET. However, in regions where conditions become more favorable for plant growth, ET may increase with increasing plant cover. Under BMRC, ET is reduced in all regions of the West but the Pacific Northwest. There the BMRC climate changes, higher temperatures at high elevations, longer growing season, and greater water supply, increase vegetative cover (Part 6). The UIUC models show a different pattern, with ET increasing dramatically in the West as the increased precipitation stimulates a denser plant cover. UIUC + Sulfate with CO_2-fertilzation shows a similar response in the West but a greater decrease in ET to the Central regions, especially in eastern Texas and Oklahoma and lower Mississippi regions. Temperature increase under UIUC + Sulfate is small (negligible when GMT = +1 °C and less than 1 °C when GMT = +2.5 °C). ET does not increase significantly with such a slight increase in temperature. CO_2-fertilization leads to increased stomatal resistance and the combined effect is a significantly lower rate of ET for the UIUC + Sulfate scenarios as compared with UIUC.

3.1.3. *Regional Hydrology*

The Major Water Resource Regions (MWRRs) are varied in their climate and hydrologic characteristics. Change in water yield and ET due to forcing by GCM, GMT and [CO_2] are reported for each MWRR in Tables I and II. Baseline water yields are given to illustrate the variety of hydrologic regimes that characterize the conterminous U.S. Water yields decline in all MWRRs under the BMRC scenarios but increase under UIUC and UIUC + Sulfates. The magnitude of the changes is amplified by higher GMT. CO_2-fertilization increases water yield in all regions. The patterns of ET change are more varied by region than by climate change scenario. In the East, ET increases in the absence of CO_2-fertilization, but declines when it is present. In the West, ET declines under BMRC but increases under UIUC scenarios due to greater water availability.

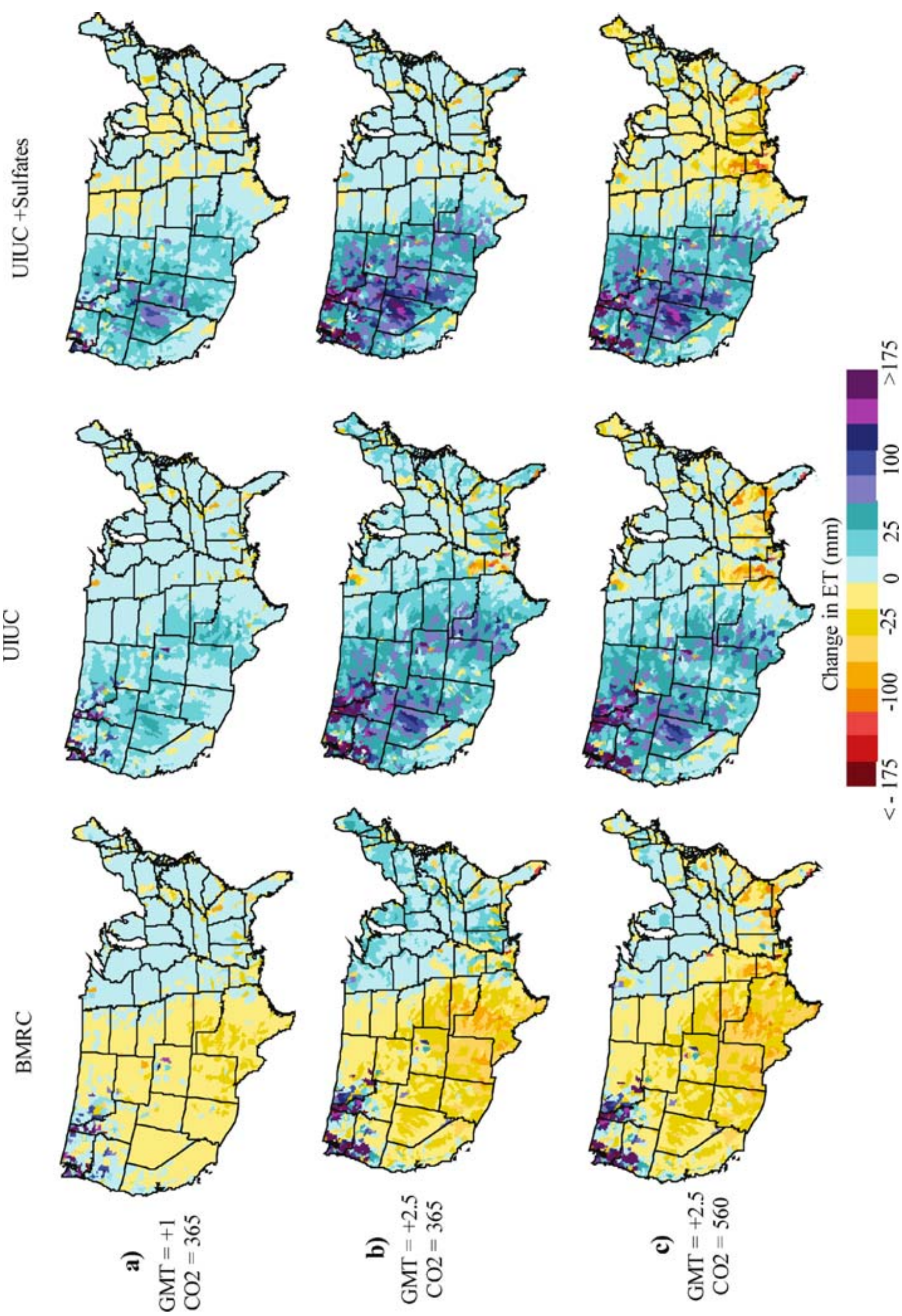

Figure 2. Evapotranspiration change from baseline (mm) for three GCMs with increasing global mean temperature (GMT) with and without the CO_2-fertilization effect.

TABLE II

Evapotranspiration (ET) at baseline and change from baseline for the 18 Major Water Resource Regions (MWRRs) under 12 scenarios of climate change

GCM	Baseline	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate	BMRC	UIUC	+Sulfate
GMT (°C)	0		1.0			1.0			2.5			2.5	
CO_2 (ppmv)	365		365			560			365			560	
MWRR	mm	Change from baseline (mm)											
New Eng.	399	7	5	3	−18	−19	−21	26	17	11	−1	−10	−15
Mid-Atl.	429	8	8	2	−6	−7	−12	19	21	14	5	7	−1
S. Atl-Gulf	566	2	4	2	−24	−22	−25	9	12	4	−17	−14	−22
G. Lakes	498	16	10	4	5	0	−8	39	25	15	27	14	4
Ohio	541	6	6	−2	−6	−5	−14	17	7	6	5	7	−6
Tenn.	547	3	2	−3	−13	−19	−19	14	−1	1	−3	−1	−15
U. Miss.	511	9	10	1	−2	−1	−10	19	14	9	7	14	−1
L. Miss.	655	2	7	−1	−31	−26	−32	2	−20	1	−29	−20	−32
Sou-R-Rai.	452	5	8	−1	−3	−1	−10	13	13	5	6	13	−3
Missouri	407	−2	23	17	−7	16	11	−8	51	39	−12	44	32
Ark-W-R.	548	−12	25	15	−24	10	0	−35	49	31	−46	31	14
TX-Gulf	584	−14	21	12	−30	2	−7	−38	42	23	−53	21	2
Rio Gr.	329	−20	23	26	−21	20	22	−53	51	52	−53	46	47
U. Colo.	241	−8	26	43	−10	23	39	−24	55	74	−24	51	69
L. Colo.	266	−11	21	37	−12	19	34	−32	45	62	−32	42	59
Gr. Basin	222	−8	37	65	−9	35	62	−21	82	106	−21	80	103
Pac. NW	230	20	43	41	10	30	28	46	110	114	46	96	98
Calif.	220	−4	12	20	−8	8	15	−13	27	35	−13	22	30

Based on their geographical location and agricultural importance, six MWRRs were selected for a comparison of water yield (WY), runoff (Q) and ET response to forcing in Figure 3. Water yield is the sum of runoff, lateral flow from the soil profile and groundwater flow from the shallow aquifer. Therefore any difference between runoff and water yield is due to a changes in the soil profile or aquifer flows. The South Atlantic-Gulf is a humid region with baseline annual water yield of ~600 mm. Water yield and runoff both decline under BMRC at GMT $= +1\,^{\circ}$C. The decline is amplified by the higher GMT and moderated by the higher [CO_2]. ET increases slightly with no CO_2-fertilization effect, but declines slightly when it is present. While WY and Q show the opposite response (increasing) under UIUC, ET responds as under BMRC. For all three GCMs, the higher GMT raises ET, but the CO_2 effect reduces stomatal conductance and lowers ET rates.

The Ohio basin is also humid at baseline (WY = 550 mm) but is cooler because of its higher latitude. ET is very similar under BMRC and UIUC, although the former predicts a lessening and the latter predicts increases in WY and Q. The BMRC decline doubles in magnitude to 15–20% at the higher GMT. ET increases with higher GMT and does not decline with CO_2-fertilization, indicating a lengthening of the growing season or larger plants due to CO_2-fertilization.

The Missouri region covers a wide range of climates in the Great Plains and Prairie states. The region ranges from humid to semi-arid under baseline conditions, averaging 500 mm of precipitation annually with a relatively high ET of 400 mm. The climate change scenarios have greater impact in this region; WY and Q decline under BMRC by 10–30% and increase under UIUC by 25–60%. The changes in ET are smaller in magnitude, declining slightly under BMRC while increasing under UIUC. ET rates are reduced in all cases by CO_2-fertilization. Under the dryer and hotter conditions of the BMRC, ET declines with higher GMT and higher [CO_2]. The lack of precipitation under BMRC may cause a decline in vegetation cover (LAI) while ET shows the opposite effect with increased precipitation under UIUC.

The Lower Colorado basin is an arid region in which temperatures vary greatly from one sub-region to another. Large decreases in Q and WY (-25 to -75%) occur under BMRC. Under UIUC increases range from 25 to more than 75%. This indicates that substantial change in the hydrologic regime of this basin is possible, although the direction is uncertain. The changes in ET are also larger, declining with BMRC and increasing with UIUC. ET decline may be a result of less water available for evaporation. CO_2-fertilization moderates the decline in ET because of increased plant cover. ET increases under UIUC as a result of greater plant cover with wetter conditions and a longer growing season. The warming may also allow for increased plant growth at higher elevations.

The Pacific Northwest region is wet under current conditions with baseline precipitation of ~700 mm/yr and water yield of ~500 mm/yr. WY and Q decline by 15% or less under BMRC and increase by about the same amount under UIUC. Increases in ET in this region are large relative to changes in WY and Q. The

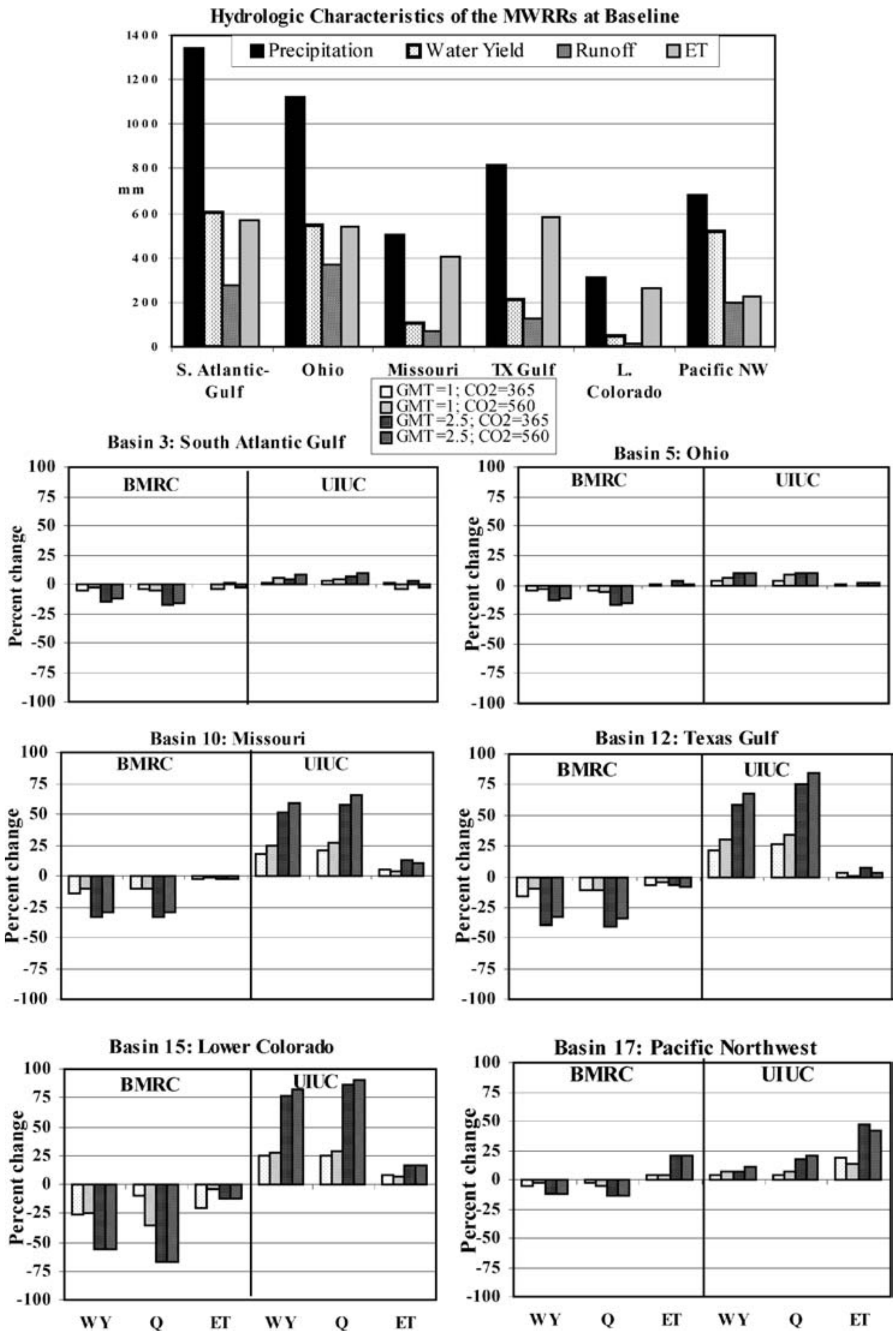

Figure 3. Water yield, runoff and ET changes in six Major Water Resource Regions (MWRRs).

increase in ET under all scenarios indicates a longer growing season in response to higher temperatures. Increases in ET are greater under UIUC because increased precipitation in the arid eastern parts of this region provide the water to evaporate.

3.2. IMPACTS ON SEASONAL WATER SUPPLY

3.2.1. *Effects of Higher GMT*

One uncertainty about water resource response to climate change concerns seasonality of the hydrologic cycle. Here we use 4-digit basins (Figure 4) in the six regions shown in Figure 3 to represent the seasonal changes in water yield at two levels of GMT. CO_2-fertilization effects are considered separately below. The selected 4-digit basins are chosen to represent the range of changes that may occur in basins nationwide, but do not necessarily accurately represent the seasonal change in the large and geographically diverse MWRRs.

BMRC warming leads to reduction in water yield in the Ogeechee–Savannah basin in all months except for a slight increase in September (Figure 5a). WY declines of as much as 10 mm occur in February and October at the higher GMT. The magnitude of change is greater with GMT $= +2.5\,^{\circ}$C while the overall pattern remains the same. With UIUC, water yield increases from baseline, with the greatest increases in winter, mid-summer and fall. Water yields decline by as much as 5 mm in the months of May and August. Sulfates in the UIUC GCM amplify the peaks

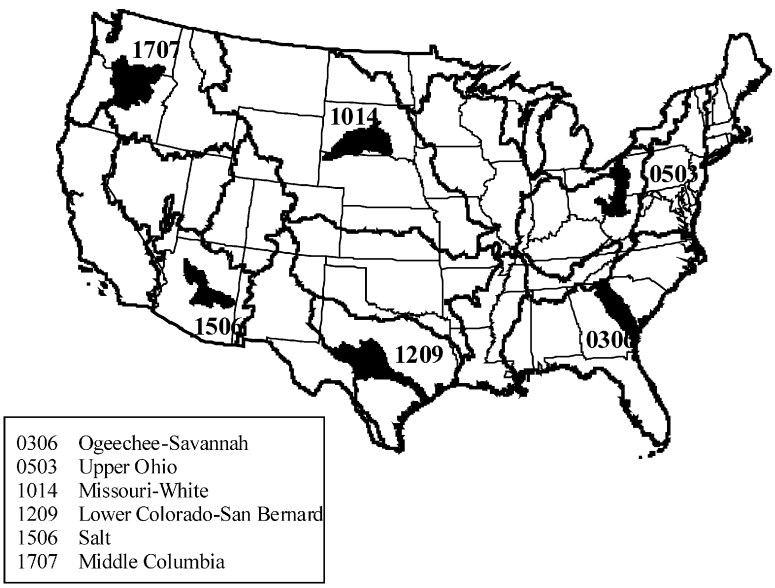

Figure 4. Location and name of the 4-digit hydrologic basins used in the analysis of changes in seasonal water yield found in Figures 5 and 6.

in months of increase. While the general trend is similar to UIUC, more months show a decline in water yield—notably March, May and August. In summer water yield increases reach 15 mm at the higher GMT.

In the Upper Ohio basin (Figure 5b), WY declines from baseline under BMRC in all months but December and February. The greatest decline (−9 mm) occurs in

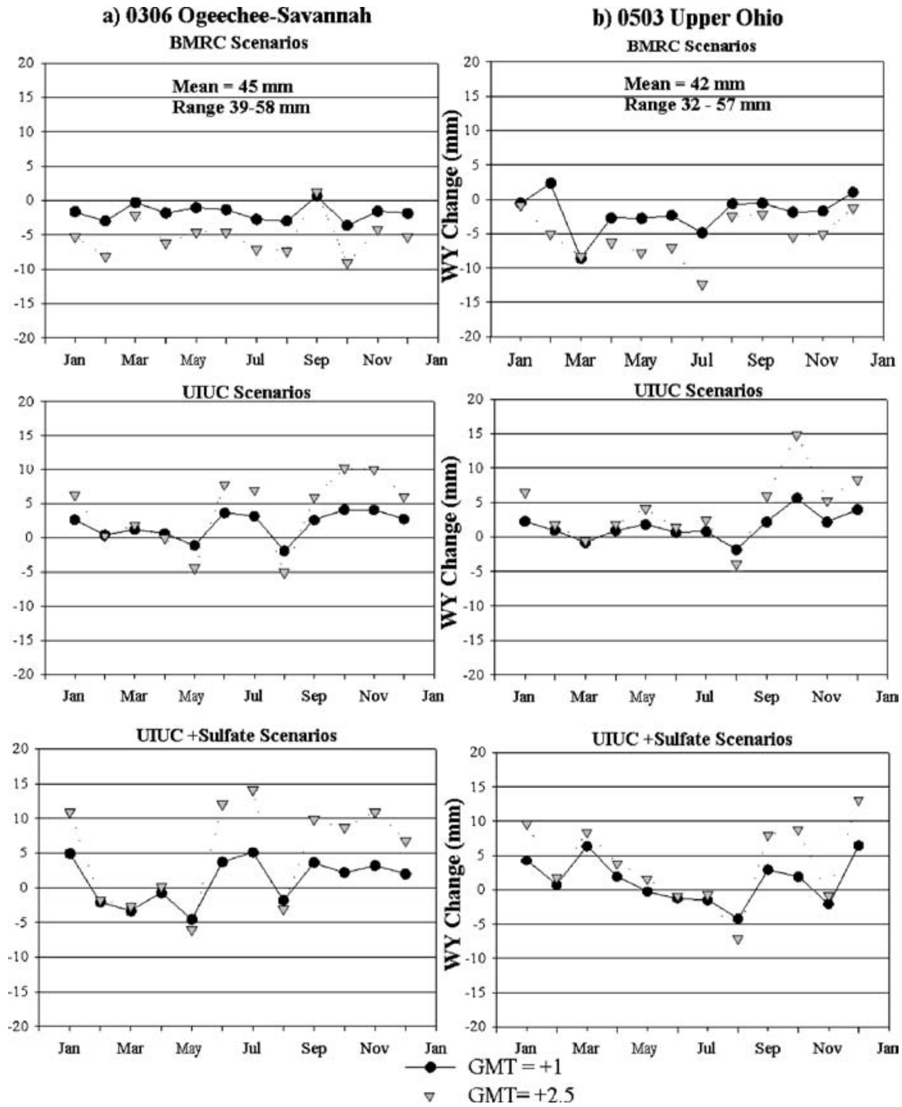

Figure 5. Seasonal water yield change from baseline in the six selected 4-digit hydrologic basins at two levels of global mean temperature (GMT) increase with the mean and range of monthly water yield given for reference.

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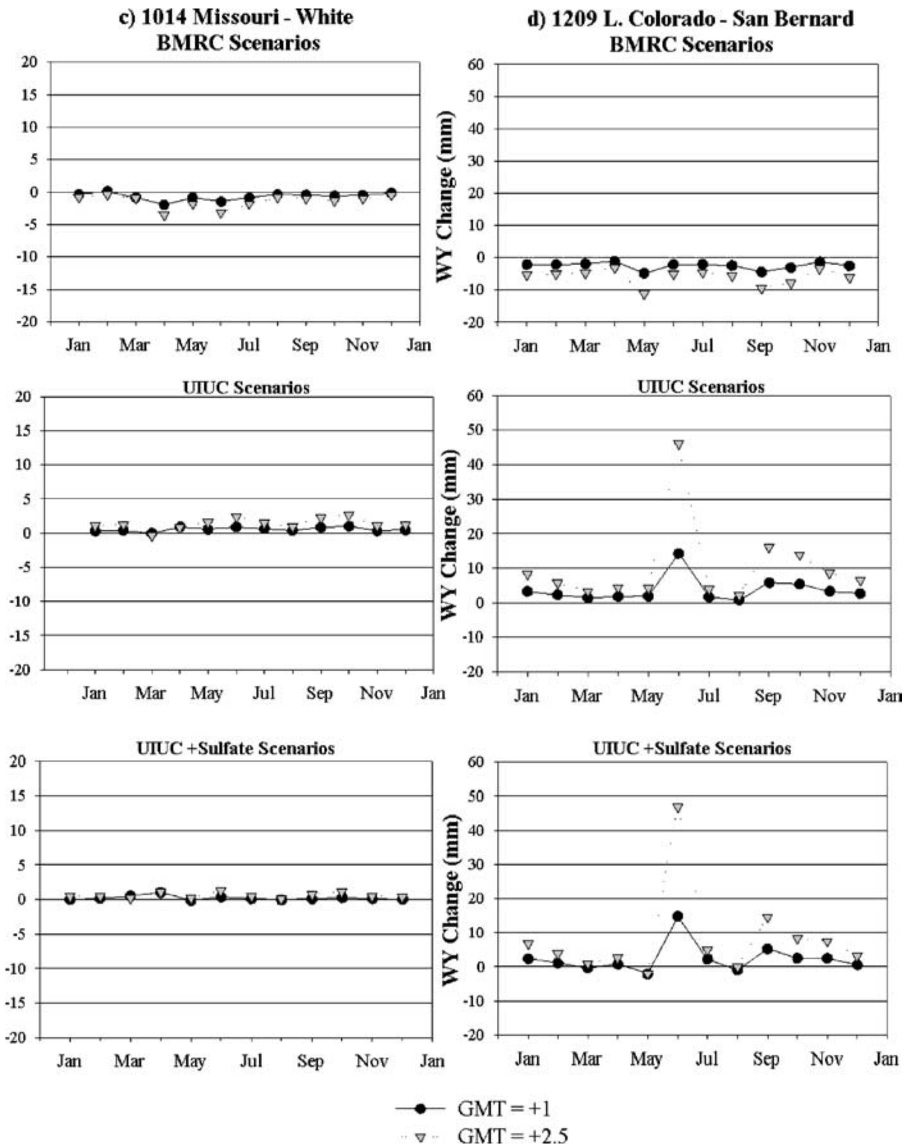

Figure 5. (*Continued on next page*.).

March. WY declines in all months at the higher GMT. While it does not decline further in March, it does decline dramatically (−13 mm) in summer, especially in July. WY increases in most seasons under the UIUC scenarios. With GMT = +1 °C, WY increases in all months but August, with the greatest increases occurring in fall. With GMT = +2.5 °C, the trends remain the same but the magnitude of winter increase is greater. Trends under UIUC + Sulfate are similar. Winter increases in WY and summer decreases are amplified. A large increase in WY occurs in March.

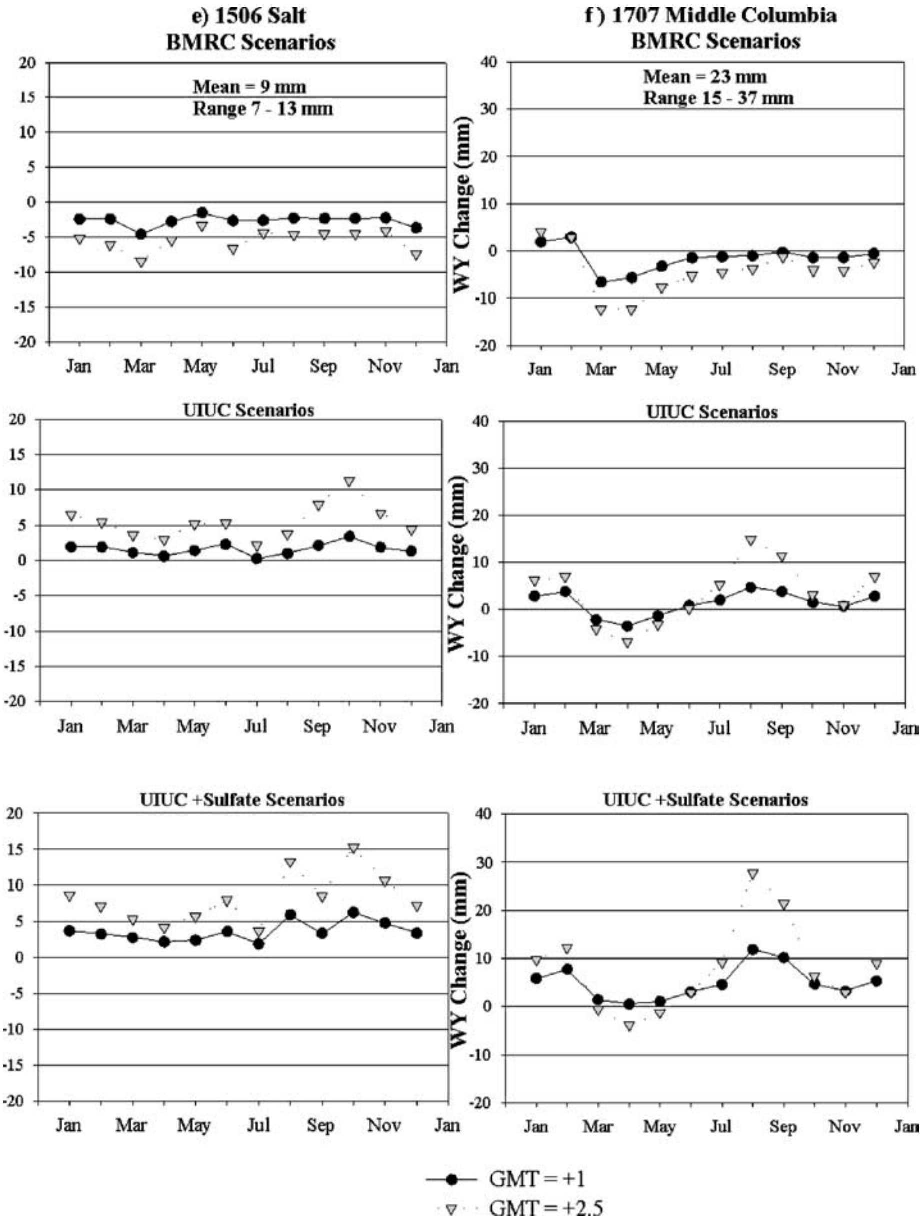

Figure 5. (*Continued*).

Water yield in the Missouri-White basin (Figure 5c) is very little changed from baseline, never exceeding ±5 mm in any month under any of the scenarios. A noticeable drying occurs in the spring and summer months under BMRC, while WY slightly increases under UIUC. In contrast, there is a sharp change in seasonal water yield under UIUC in the Lower Colorado-San Bernard basin (Figure 5d).

The UIUC models show sharp WY increases in the month of June, from 15 to 50 mm above the baseline. There is also a marked increase in fall water yield. Under BMRC, water yield declines uniformly throughout the year with greater drying in May and in the fall months.

Water yields decline noticeably throughout the year in the Salt basin under BMRC (Figure 5e). The greatest declines occur in spring with a dip in December. The UIUC scenarios cause an increase in water yield. The increase is substantial under GMT = +1 °C during June and October. The increases are greater with GMT = +2.5 °C, peaking at +10 mm in October. The trend under UIUC + Sulfates is similar to UIUC alone but with larger increases. Also, there is a more sustained increase through the fall and winter months.

In the Middle Columbia basin (Figure 5f) distinct changes occur in WY patterns under all three GCMs and at both GMT levels; i.e., an increase in water yield in the winter and a decline in spring. Under the UIUC scenarios the summer increase is amplified at GMT = +2.5 °C. With the sulfate effect included, summer and winter increases are more prominent and the spring decline slightly less so. The winter increase and spring decrease in all of the scenarios indicates a greater proportion of winter precipitation falling as rain and a smaller snowpack melt in the spring. The effect varies by degree according to the temperature increase in a given scenario. The increase in temperature under UIUC + Sulfate is very small; hence, this effect is least apparent under this scenario (see Part 1, Figure 5). The increase in late summer and fall precipitation under UIUC would radically change the current pattern of wet winter–dry summer climate of this region.

3.2.2. *Effects of CO_2-Fertilization*

We selected two basins with significant changes in water yield, the Upper Ohio and Middle Columbia, to examine whether CO_2-fertilization notable alters the changes in water yield due to GCM and GMT. We examined only BMRC and UIUC results for this purpose. In the Upper Ohio (Figure 6a) under the BMRC scenarios, enhanced CO_2 causes a slight increase in WY in the winter months and a greater WY increase from June to November. The effect of elevated [CO_2] with the UIUC scenario is much greater, up to 2 mm, and is most apparent in the spring and summer growing season.

The fertilization effect is less apparent in the Middle Columbia basin (Figure 6b), <1 mm in all months. This region receives, on average, less precipitation than the Upper Ohio. The Pacific Northwest is sharply divided into a humid region west of the Cascade mountains and arid land to the east. The higher [CO_2] influences water yield by reducing plant demand for water, and the expected result is higher water yield. However, increased precipitation in arid regions may boost vegetative growth, causing a decline in water yield as the growing plant population consumes more water. The interaction of these two effects results in little measurable increase in water yield with enhanced CO_2 in the Pacific Northwest.

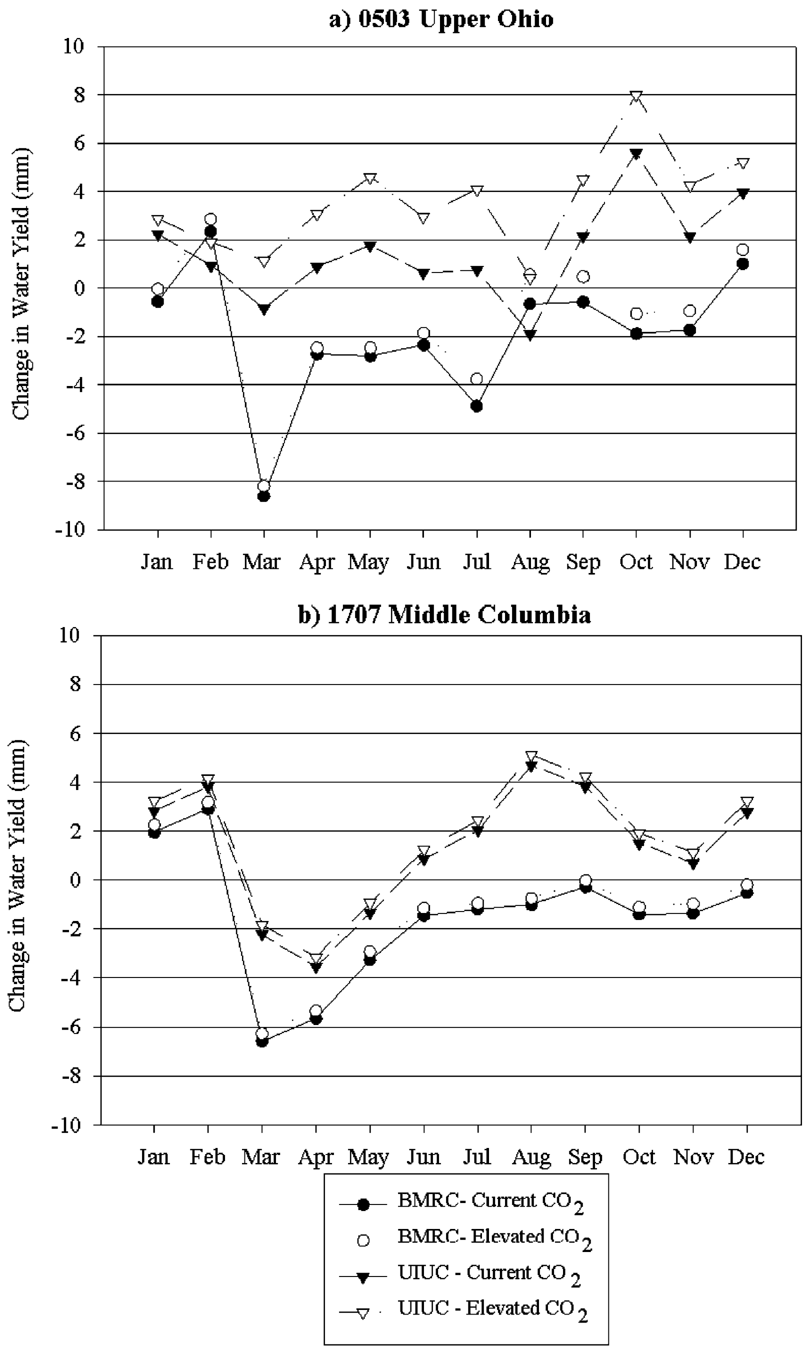

Figure 6. Seasonal water yield change from baseline for two GCMs with and without the CO_2-fertilization effect.

TABLE III

Coefficients of variation (CV) for interannual water yield in 8-digit basins representing each of the 18 Major Water Resource Regions (MWRRs) of the conterminous U.S.A.

GCM			Baseline	BMRC	UIUC	UIUC +S	BMRC	UIUC	UIUC +S	BMRC	UIUC	UIUC +S	BMRC	UIUC	UIUC +S
GMT (°C)			0		1			1			2.5			2.5	
CO_2 (ppmv)			365		365			560			365			560	
HUA8	Basin	State	Coefficient of variation (CV)												
01060001	Presumpscot	ME	27.5	28.3	27.8	27.7	26.9	26.4	26.3	29.5	27.4	27.3	28.3	25.5	25.6
02050206	Susquehanna	PA	13.2	12.9	13.7	13.5	13.1	13.7	13.5	12.5	14.2	14.2	12.2	14.3	14.3
03060201	Ogeechee	GA	17.8	18.2	17.8	16.8	16.7	16.5	15.7	17.9	17.3	16.7	16.4	16.5	15.5
04030108	Menominee	MI	14.6	15.1	14.1	14.6	13.8	12.9	13.3	17.0	13.9	14.5	15.3	12.7	13.3
05090201	Ohio	OH	21.1	22.1	20.8	21.6	21.2	21.9	20.9	22.6	20.6	21.5	21.8	20.6	21.1
06040002	Duck	TN	21.5	21.9	21.8	21.6	21.8	19.7	21.6	22.8	22.4	22.3	22.7	22.4	22.2
07080103	Wapsipinicon	IA	33.1	33.4	32.5	34.3	32.2	31.5	32.9	34.0	31.5	34.8	32.2	31.5	33.4
08030207	Sunflower	MS	33.6	35.5	33.5	33.6	34.2	32.7	32.8	39.6	32.9	34.0	38.1	32.9	33.3
09020309	Snake	MN	53.3	56.9	50.7	49.9	56.0	51.7	49.7	64.5	50.1	51.5	64.1	50.1	51.3
10140201	White	NE	41.7	42.8	39.6	40.1	42.7	39.4	39.8	46.2	38.0	38.8	45.4	37.3	38.6
11060006	Black	OK	71.1	79.1	59.3	58.7	75.1	56.3	55.7	86.8	48.9	49.6	84.9	47.4	47.6
12090202	Llano	TX	37.1	39.6	30.1	30.3	39.1	29.7	29.9	43.7	25.4	25.3	43.3	25.3	25.4
13050003	Tularosa	NM	77.0	91.4	80.1	77.8	90.3	79.3	76.7	124.4	84.3	80.5	124.4	83.1	79.0
14060006	Willow	UT	95.0	106.5	86.7	76.9	106.7	85.8	75.5	139.6	68.7	51.9	139.6	64.2	50.2
15070102	Agua Fria	AZ	74.5	84.2	66.9	61.0	83.2	66.1	60.0	106.0	54.9	50.2	106.0	54.5	49.7
16060006	Little Smoky	NV	66.1	79.8	65.4	64.8	78.8	64.5	64.2	109.6	71.2	70.3	109.6	70.3	70.4
17030001	Yakima	WA	29.0	28.0	26.1	26.4	27.8	26.0	26.3	31.6	27.0	26.5	31.6	26.5	26.2
18040012	Mokelumne	CA	40.1	41.9	40.4	39.4	41.6	40.2	39.1	43.6	39.5	38.5	43.6	39.5	38.4

3.3. INTERANNUAL VARIABILITY IN WATER YIELD

To assess the effects of the climate change scenarios on variability of water yield (WY) we calculated the coefficients of variation (CV) for selected 8-digit basins in each of the 18 MWRRs, simulated over 30 yr (Table III). Interannual WY variability is greatest under baseline conditions in the West, particularly in the Upper and Lower Colorado, the Rio Grande, and the Arkansas-White-Red MWRRs. Water yields are least variable in the East, the Mid-Atlantic, the South Atlantic-Gulf and the Great Lakes. Climate change does not greatly alter the relative variability in basin water yield. But variability does change within the individual basins. As with precipitation and water yield, changes increase in magnitude with increased GMT. CO_2-fertilization decreases variability within each level of GMT.

In general, changes in variability of WY are small, but trends under the climate change scenarios are evident. CV increases slightly under BMRC scenarios with declining water yields and decreases under UIUC scenarios as water yields increase. CV increases under UIUC + Sulfate in Eastern basins while it declines in Western regions with their high baseline CVs. The Mid-Atlantic region is the exception with declining variability under the BMRC scenarios but increasing variability with the UIUC scenarios. The low variability in water yields in the Tennessee region is increased slightly under UIUC as well as under BMRC, indicating that the stability of water flow in this humid region is not at great risk of becoming more variable. By contrast, CV in the Pacific Northwest region declines under almost all scenarios except when severe drying occurs under BMRC at GMT = +2.5 °C.

The changing variability under these scenarios indicates that if conditions become dryer, as they do under BMRC, variability may increase, whereas if water yield increases, as under UIUC, variability may decline. This trend is consistent with historical observations in hydrology in which interannual variability is greatest in the most arid regions.

4. Conclusions

The hydrology of the conterminous U.S. will likely change with global climate change but, because of differences projected by the GCMs, we have used to drive the HUMUS model, our simulations disagree as to whether the U.S. will experience shortfalls or surpluses of water and which regions will be most strongly affected. Currently, semi-arid regions, primarily in the western U.S., will be the first to experience notable changes in regional hydrology. The magnitude of changes in water yield, runoff and evapotranspiration is much greater, often exceeding ±50% of baseline levels in regions where water is currently in short supply. Although the impact of these changes will greatly depend on their timing and duration, changes of this magnitude may require substantial adaptation by water resource managers to cope with increased severity and duration of droughts and/or floods.

In the humid regions of the country, the scenarios suggest less dramatic, but nonetheless significant, changes in both the short and long term (GMT = +1.0 and +2.5 °C). In addition, interannual variability in the water supply will also change slightly, most significantly in arid western regions. If a drying such as is predicted in many BMRC scenarios does occur, variability is likely to increase. If water yields increase as projected by the HUMUS simulations driven by UIUC scenarios, variability may decline. Because of the considerable uncertainty about the sign and size of changes in water supplies, it is important for water resource management to be flexible and adaptable. Traditionally, water resource management has relied on the historic record to project the frequency of severe water supply anomalies. The kinds of changes described in this paper suggest the need to plan for more events outside the range of past experience.

In this analysis of water resources, we have assumed natural streamflow and have not considered withdrawals of water for human uses, changing demand or competition between uses. In Part 5, we will examine the sufficiency of these future water supplies in the U.S. for irrigated agriculture, the major consumptive user of freshwater. This analysis should help determine whether changes in water resources will require substantial changes be made in agricultural production practices in the U.S.

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