Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO$_2$

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Abstract Previous studies have demonstrated that changes in temperature and precipitation (hereafter climate change) would influence river discharge, but the relative importance of climate change, land use, and elevated atmospheric CO$_2$ have not yet been fully investigated. A process-based projection for the Mississippi River basin suggests that river discharge would be substantially enhanced (10.7–59.8%) by the 2090s compared to the recent decade (2000s), although large discrepancies exist among different climate, atmospheric CO$_2$, and land use change scenarios. Our factorial analyses further indicate that the combined effects of land use change and human-induced atmospheric CO$_2$ elevation on river discharge would outweigh climate change effect under the high-emission scenario (A2) of the Intergovernmental Panel for Climate Change, while climate change would still play the dominant role under the low-emission scenario (B1). This study highlights the important role of anthropogenic factors in influencing future hydrological processes and water resources.

1. Introduction

River discharge is a critical component of the global water cycle and plays an important role in driving the climate system, as freshwater movement into the ocean may influence oceanic circulation patterns [*Durack et al.*, 2012]. It also affects the distribution of water resources, nutrient export, and phytoplankton growth, therefore accounting for water quality in inland waters and the coastal ocean [*Bauer et al.*, 2013]. Over recent years, much concern has been raised about how unprecedented changes in temperature and precipitation (hereafter climate change), land use/land cover, and atmospheric CO$_2$ concentration may affect the discharge of global major rivers [*Gerten et al.*, 2008]. Numerous studies have investigated the historical changes in river discharge and the underlying mechanisms at regional or global scales using a range of approaches, including hydrological modeling, gauge stations data analysis, regression analysis, and process-based ecosystem modeling [*Jha et al.*, 2004; *Nakaegawa et al.*, 2013; *Shi et al.*, 2011; *Zhang and Schilling*, 2006]. A growing consensus is that a warming climate might result in hydrological intensification (increases in evapotranspiration and river flow) globally due to warming-triggered increases in evaporation and precipitation [*Huntington*, 2006; *Milliman et al.*, 2008], although debate remains about the magnitude and trends of this change [*Shi et al.*, 2011]. Studies also demonstrate that increased atmospheric CO$_2$ concentration generally reduces leaf stomatal conductance and therefore reduces the amount of evapotranspiration [*Medlyn et al.*, 2001; *Shi et al.*, 2011]. On the other hand, CO$_2$ fertilization effects may stimulate the production of more leaf area which tends to increase the amount of transpiration from plants to the atmosphere; a mitigating factor to this is that the extra leaf area would shade more the underlying ground from direct sunrays, potentially reducing the amount of soil evaporation [*Betts et al.*, 2007].

Previous studies involving future projections of river discharge have generally used hydrological models or coupled atmosphere–ocean general circulation models at very coarse spatial resolution (>1°), in which ecological and plant physiological processes are generally oversimplified. Insufficient resolution in those studies makes it difficult to account for spatial heterogeneity in river networks and land surfaces, thereby introducing large uncertainties in estimating water fluxes at regional scales. Moreover, because of limitations in data availability or modeling capabilities, most previous projection studies have focused on climate

change or atmospheric CO_2 and excluded other major influencing factors, such as land use and land cover change. It has been shown that land use change (e.g., intensive crop expansion and urbanization) would enhance water demands from the increasing human population with higher living standards and therefore may result in considerable changes in river discharge from river to ocean [*DeFries and Eshleman*, 2004]. Some global level studies have highlighted the role of land use change in global runoff and river flow [*Piao et al.*, 2007; *Shi et al.*, 2011], but how future land use would contribute to changes in river discharge still remains far from clear. Given that warmer climatic conditions and more intensive land use change have been projected to occur in nearly all major regions across the globe, there is an urgent need to realistically quantify the potential magnitude and temporal variations of river discharge in the future and to identify the relative contribution of various influencing factors. This would provide not only a deeper insight into how hydrological dynamics would respond to natural and anthropogenic drivers at broad scales but also a scientific basis for enhancing our ability to sustainably use water resources and mitigate and adapt to future climate change.

As one of the largest river basins and the most productive farming regions in the world, the Mississippi River basin (MRB) has experienced substantial climate change and intensive land use change and is projected to undergo further rapid changes in the future [*Foley et al.*, 2004; *Sohl and Sayler*, 2008]. The MRB also has rich data sets available for exploring the role of different controlling factors and therefore provides an ideal place to investigate potential changes in the hydrological cycle as influenced by the combination of natural and anthropogenic driving forces. In a previous study, we estimated historical trends in hydrological fluxes over the drainage basins of the Gulf of Mexico [*Liu et al.*, 2013]. In this study, we used a process-based ecosystem model—the Dynamic Land Ecosystem Model (DLEM) [*Tian et al.*, 2010a] to examine future changes in discharge from the Mississippi River and to evaluate the relative roles of future climate, atmospheric CO_2, and land use during 2011–2099.

2. Methods

2.1. Model Description and Evaluation

The DLEM model is a highly integrated, process-based terrestrial ecosystem model which couples biophysical characteristics, plant physiological processes, biogeochemical cycles, and vegetation dynamics processes to make daily, spatially explicit estimates of carbon, nitrogen, water fluxes, and pool sizes in the terrestrial ecosystems from site to regional to global scales [*Tian et al.*, 2010a, 2010b, 2011]. Recently, we updated the model to the DLEM version 2.0, which is characterized by cohort structure, multiple soil layer processes, coupled carbon, water and nitrogen cycles, enhanced land surface processes, and dynamic linkages between terrestrial and riverine ecosystems. More detailed hydrological processes and parameterization in the DLEM model were described in our previous publication [*Liu et al.*, 2013; *Tian et al.*, 2010a].

Model parameterization for the continental U.S. and North America, including the MRB, has been well described in our previous work [*Liu et al.*, 2013; *Tian et al.*, 2010b]. In particular, our previous Gulf of Mexico study has shown that DLEM-simulated evapotranspiration, runoff, and streamflow agree well with the observations [*Liu et al.*, 2013]. Here we further evaluated the DLEM-simulated water discharge from the Mississippi River basin against the U.S. Geological Survey observations for the period of 1992–2010. The comparisons demonstrate that the DLEM model is generally capable of capturing magnitude and interannual variations of water discharge ($R^2 = 0.84$, P value < 0.05, see Figure S1 in the supporting information).

2.2. Input Data

In this study, we used climate, land use, and CO_2 data that are all consistent with assumptions under the A2 and B1 scenarios selected from the Special Report on Emission Scenarios (SRES); A2 and B1 scenarios represent high and low levels of population growth, economy, and energy consumption, respectively, and therefore are on opposite ends of the spectrum regarding projected temperature and atmospheric CO_2 concentration increases. The future climate data are from the Daily Statistically Downscaled World Climate Research Program (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) Climate Simulations, which were used in the Third U.S. National Climate Assessment [*Melillo et al.*, 2014]. These data sets are based on the WCRP's CMIP3 multimodel data set and are spatially "downscaled" from 2° to a finer 0.125° spatial

Table 1. Simulation Protocol for Determining the Effects of Climate, Land Use, and CO_2 on River Discharge[a]

| | | Climate (Three GCMs) | | | | | | Land Use | | CO_2 | |
| | | CCSM3 | | ECHAM | | CCCMA | | | | | |
Simulation Experiments		A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
E1	E1_CCSM3_A2	Yes	-	-	-	-	-	Yes	No	Yes	No
	E1_CCSM3_B1	-	Yes	-	-	-	-	No	Yes	No	Yes
	E1_ECHAM_A2	-	-	Yes	-	-	-	Yes	No	Yes	No
	E1_ECHAM_B1	-	-	-	Yes	-	-	No	Yes	No	Yes
	E1_CCCMA_A2	-	-	-	-	Yes	-	Yes	No	Yes	No
	E1_CCCMA_B1	-	-	-	-	-	Yes	No	Yes	No	Yes
E2	E2_CCSM3_A2_CLM	Yes	-	-	-	-	-	No	No	No	No
	E2_CCSM3_B1_CLM	-	Yes	-	-	-	-	No	No	No	No
	E2_ECHAM_A2_CLM	-	-	Yes	-	-	-	No	No	No	No
	E2_ECHAM_B1_CLM	-	-	-	Yes	-	-	No	No	No	No
	E2_CCCMA_A2_CLM	-	-	-	-	Yes	-	No	No	No	No
	E2_CCCMA_B1_CLM	-	-	-	-	-	Yes	No	No	No	No
	E2_land_use_A2	No	No	No	No	No	No	Yes	No	No	No
	E2_land_use_B1	No	No	No	No	No	No	No	Yes	No	No
	E2_CO$_2$_A2	No	No	No	No	No	No	No	No	Yes	No
	E2_CO$_2$_B1	No	No	No	No	No	No	No	No	No	Yes

[a]E1 allows all environmental factors (climate, land use, and CO_2) to change over time using three climate models (CCSM3, ECHAM, and CCCMA) and two emission scenarios (A2 and B1); E2 allows one environmental factor to change over time while holding the rest constant at initial level using three climate models and two emission scenarios.

resolution, covering the entire continental U.S. [*Stoner et al.*, 2013]. We adopted projected future climate data from three general circulation models (GCMs) (Community Climate System Model version 3.0 (CCSM3), European Centre/Hamburg (ECHAM), and Canadian Centre for Climate Modelling and Analysis (CCCMA)) under the SRES A2 and B1scenarios. The daily climate variables include minimum temperature, maximum temperature, and precipitation. To keep our simulations for the projected period (2011–2099) consistent with the historical/contemporary period (1992–2010), we further statistically downscaled to a resolution of 5 arc min.

In the new version of the model (DLEM 2.0), a dynamic cohort approach is adopted to represent land use and land cover changes at the grid level [*Liu et al.*, 2013]. We assume that each grid cell is initially covered by undisturbed potential vegetation and other land cover types (i.e., bare land, glacier, river, lake, and ocean). When a disturbance occurs (e.g., from forest to cropland), a new cohort is formed, and the disturbed land area within the grid cell is then proportionally subtracted from the undisturbed potential vegetation. Spatially explicit land use databases from 1992 to 2099 under the A2 and B1 scenarios were derived from the Forecasting Scenarios of Future Land Cover (FORE-SCE) model [*Sohl and Sayler*, 2008]. In this study, we generated 5 arc min fraction land use data by reprojecting and aggregating the 250 m FORE-SCE-projected scenarios using Environmental Systems Research Institute ArcInfo 10. The projected CO_2 concentrations under the A2 and B1 scenarios are derived from the Intergovernmental Panel for Climate Change Data Distribution Center (http://www.ipcc-data.org/observ/ddc_co2.html). Other data sets, including historical nitrogen deposition, tropospheric ozone, land management practices, river network, soil, and topographic layer, are consistent with our previous work [*Liu et al.*, 2013; *Tian et al.*, 2010b].

2.3. Simulation Experiments and Implementation

To project potential changes in river discharge and quantify the relative contributions of the three major environmental factors (climate, land use/land cover, and atmospheric CO_2 concentration), we performed two sets of simulations (16 runs in total) (Table 1). In the first set of simulations, we accounted for all historical and projected changes in climate, land use, and atmospheric CO_2 over the study period (E1, six simulations, and three GCMs times two scenarios). In the second set of simulations, we allowed one of the driving environmental factors to change over time, while holding the rest constant at an initial level, for quantifying the individual factor effects on river discharge (E2, six climate only, two land use only, and two CO_2 only). Our simulations began with an equilibrium run, in which the environmental conditions in the year 1991 were
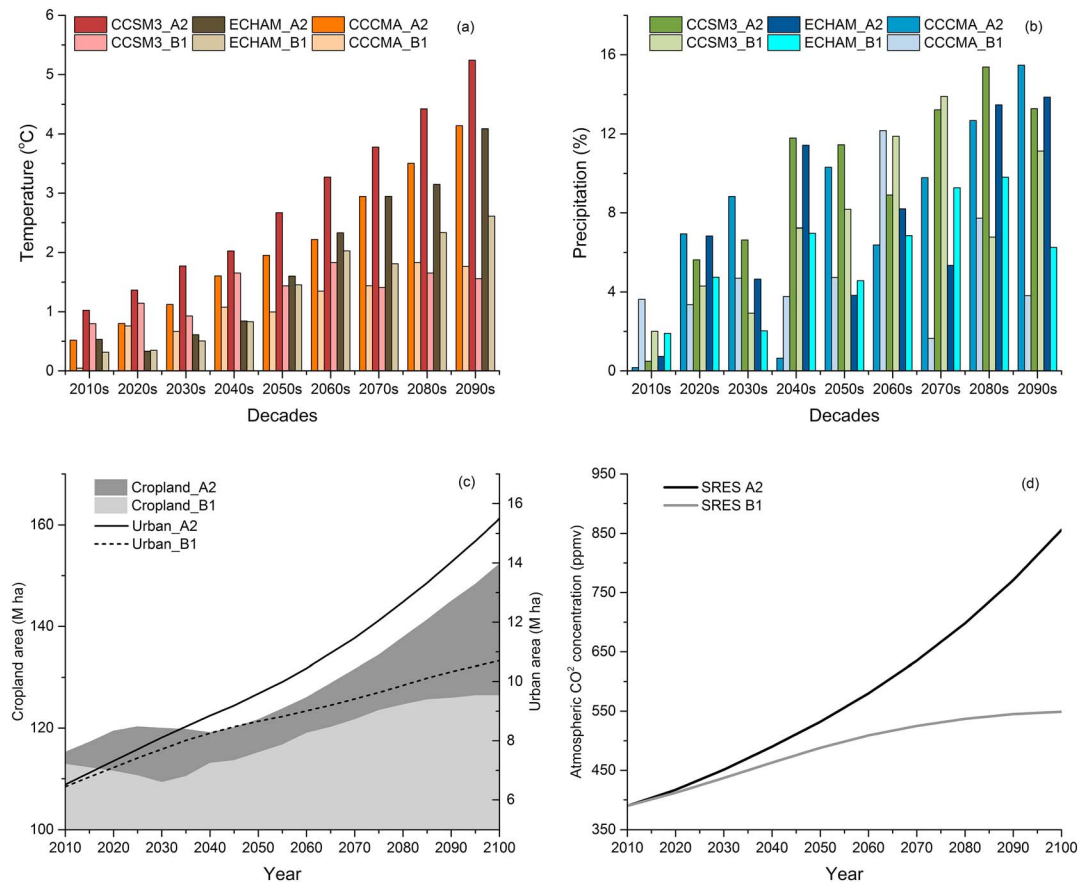
Figure 1. The 21st century scenarios of multiple environmental changes across the Mississippi River basin. (a and b) Changes in temperature (°C) and precipitation (%) during 2011–2099 relative to the 10-year average (2000–2009) and (c and d) projected changes in land use and atmospheric CO_2 concentration under the A2 and B1 scenarios.

used to drive the model in order to achieve an equilibrium state (i.e., the interannual variation of net fluxes less than $0.1\,g\,C\,m^{-2}\,yr^{-1}$ for carbon, $0.1\,g\,N\,m^{-2}\,yr^{-1}$ for nitrogen, and $0.1\,mm\,m^{-2}\,yr^{-1}$ for water within a 50 year simulation cycle). For the equilibrium run, the climate conditions were taken as the average between 1991 and 2010; other environmental factors, including land use, atmospheric CO_2 concentration, and nitrogen deposition, were held static for the year 1991. Three spin-ups over the 20-year period (1991–2010) were conducted to reduce the biases in the transient runs. The model was then fed by the time series of input data sets in the transient mode. The historical simulation from 1992 to 2010 was used for model validation and evaluation. Our analyses mainly focus on the future period of 2011–2099.

3. Results and Discussions

3.1. Environmental Changes and River Discharge

Our analyses show that the MRB would experience dramatic changes in climate, atmospheric CO_2 concentration, and land use by the end of this century, especially under the A2 scenario (Figure 1). The three GCMs predict increases in annual temperatures (ensemble mean from the three GCMs) of 1.30°C (1.00 to 1.45°C, B1 scenario) to 2.07°C (1.60 to 2.67°C, A2 scenario) by the 2050s and 1.98°C (1.56 to 2.61°C, B1 scenario) to 4.49°C (4.09 to 5.24°C, A2 scenario) across the study area by the 2090s, relative to the recent decade (2000s). Precipitation is projected to increase (ensemble mean from three GCMs) between 5.83% (4.57~8.18%) and 8.53% (3.83~11.45%) by the 2050s and between 7.07% (3.81~11.13%) and 14.21% (13.28~15.47%) by the 2090s, with substantial interannual fluctuations and spatial variations (Table S1 in the supporting information). Across the MRB, cropland is projected to undergo a rapid increase (32%) by the end of this century relative to the 2010 level under the A2 scenario, with a slight increase (11%) under the
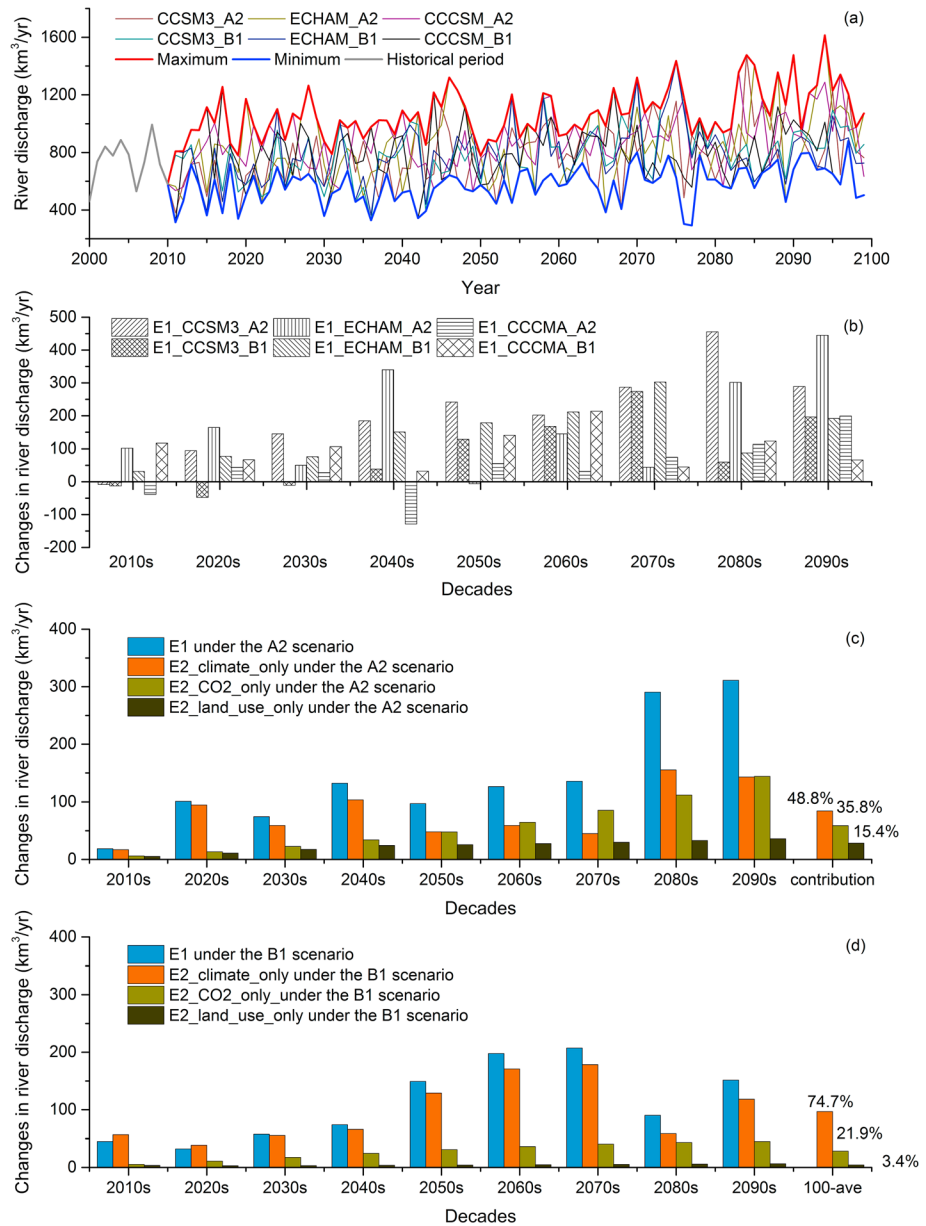
Figure 2. Projected Mississippi river discharge over the 21st century and its environmental controls. (a and b) Projected interannual variations and decadal changes in annual river discharge from the E1 simulation experiments relative to the 2000–2009 average. (c and d) Relative contributions of future climate, land use, and atmospheric CO_2 concentration to projected changes in river discharge under the A2 and B1 scenarios.

B1 scenario. Additionally, urban areas are projected to increase by 138% and 66% under the A2 and B1 scenarios, respectively.

According to the combined simulations (E1; Figure 2a), future changes in climate, land use/land cover, and atmospheric CO_2 concentration would result in a significant increasing trend in river discharge throughout the 21st century. Based on the Mann–Kendall trend test, the projected river discharge from all E1 simulations show significant upward trends, with a rate of 1.7–4.1 km^3/yr during 1992–2099 ($P < 0.01$), except CCCMA under the B1 scenario. Projected changes in future river discharge would largely vary among the different environmental scenarios and show substantial interannual variations due to climate variability. The highest estimation (red line in Figure 2a) is 2.5 times that of the lowest estimation (blue line in Figure 2a) at the end of this century. Projected decadal changes of river discharge relative to the 10-year average

Table 2. Projected Decadal Changes in River Discharge From the Mississippi River Basin According to Different Simulation Experiments[a]

Simulation Experiments	Decades	A2 Projected Decadal Changes in River Discharge (km³/yr)			B1 Projected Decadal Changes in River Discharge (km³/yr)		
		CCSM3	ECHAM	CCCMA	CCSM3	ECHAM	CCCMA
E1	2000s	745	745	745	745	745	745
	2050s	986.7 (32.4%)	739.5 (−0.7%)	803.3 (7.8%)	873 (17.2%)	923.7 (24.0%)	899.1 (20.7%)
	2090s	1034.1 (38.8%)	1190.2 (59.8%)	947.1 (27.1%)	941.2 (26.3%)	936.9 (25.8%)	824.7 (10.7%)
E2_climate	2000s	740	740	740	740	740	740
	2050s	908.6 (22.8%)	703.8 (−4.9%)	745.8 (0.8%)	839.2 (13.4%)	905.1 (22.3%)	846.5 (14.4%)
	2090s	849.7 (14.8%)	1018.3 (37.6%)	774.9 (4.7%)	898.6 (21.4%)	898.2 (21.4%)	762.1 (3.0%)
E2_land use	2000s	640				638.9	
	2050s	663.7 (3.7%)				643.1 (0.6%)	
	2090s	673.3 (5.5%)				645.9 (1.0%)	
E2_CO2	2000s	640.8				640.8	
	2050s	687.5 (7.3%)				671.8 (4.8%)	
	2090s	786.5 (22.7%)				686.0 (7.1%)	

[a]E1 allows all environmental factors (climate, land use, and CO2) to change over time using three climate models (CCSM3, ECHAM, and CCCMA) and two emission scenarios (A2 and B1); E2 allows one environmental factor to change over time while holding the rest constant at initial level using three climate models and two emission scenarios.

(2000–2009) show different levels of increase under both A2 and B1 scenarios (Figure 2b). Most projections show substantial upward trends in river discharge in the late 21st century, with the largest increase under CCSM3 in the 2080s and ECHAM in the 2090s under the A2 scenario. Although there are obvious differences in river discharge among the GCM model projections, all the three GCM climate-driven changes in decadal means of river discharge since the second half of the 21st century uniformly show large increases in river discharge under the A2 scenario, with higher increases in the 2080s and 2090s under the A2 scenario than those under the B1 scenario.

Our results show larger differences in river discharge among the GCMs than those under the two scenarios, except in the 2090s, while projected river discharge under the A2 scenario would be all significantly greater than those from the B1 scenario. This finding is supported by a recent global analysis, which indicated that the differences in the computed changes of annual runoff caused by different climate models are even larger than those due to the different scenarios [*Wuebbles et al.*, 2013]. On one hand, these findings illustrate large uncertainties in future climate projection; on the other hand, our results also provide evidence for hydrological intensification even for the low-emission scenario (B1), especially if relatively lower temperatures coincide with high precipitation. Even greater increases in river discharge under the A2 scenario over the last 2 decades are consistent with environmental scenarios at the end of this century, which are characterized by intensive land use, elevated atmospheric CO_2 concentration, and increased precipitation resulting from warming climate.

3.2. Relative Contributions of Climate, Land Use, and CO_2 to Projected Changes in River Discharge

We used single-factor simulation experiments (E2 in Table 1) to distinguish

the potential effects of each individual factor (climate, land use, and atmospheric CO_2) on projected river discharge in the MRB. Most climate-only simulations (E2 group) show an upward trend of river discharge over the late 21st century but with less magnitude than projected in the E1 group (Figure 2c and Table 2). Compared to the recent 10 year average, future increases in river discharge (averaged over the three GCMs) induced by climate change alone are projected to be approximately 19.0% (between 4.7% and 37.6%) and 15.2% (between 3.0% and 21.4%) by the end of this century (2090s) under the A2 and B1 scenarios, respectively, although large discrepancies exist among results from the different GCMs (Table 2). These projected increases in river discharge are comparable in magnitude to that of a recent study using an atmospheric general circulation model, which suggested that river discharge in the MRB would have an increase of 10.5% by the end of this century under the A1B scenario, an intermediate emission scenario [*Nakaegawa et al.*, 2013]. Our results also agree with those of previous studies that were based on coupled atmosphere–ocean GCMs and hydrological models [*Doll and Schmied*, 2012; *Nijssen et al.*, 2001]. These findings point to a general consensus that warming climate would accelerate the hydrological cycle among land, atmosphere, and ocean domains, therefore resulting in global hydrological intensification (such as substantial changes in evapotranspiration, runoff, and river flow) [*Huntington*, 2006; *Milliman et al.*, 2008].

The E2 simulations attribute a substantial proportion of the total projected increases in river discharge to climate change (48.8% and 71.9% under the A2 scenario and the B1 scenarios, respectively; each E2 experiment was divided by the sum of all E2 experiments to get the percentages, Figures 2c and 2d). On further analyses, although temporal variations in projected river discharge are dominated by climate change during 2011–2099, land use change and atmospheric CO_2 elevation together were found to have comparable impacts and further enhanced the increase of river discharge, particularly under the A2 scenario (Figure 2c). Across the study region, substantial cropland expansion and urban sprawl are projected to occur over the 21st century (Figure 1c), which would notably alter surface water balance and the portioning of precipitation into evapotranspiration, runoff, and groundwater flow [*Costa et al.*, 2003].

Our single-factor simulations (E2) suggest that land use change, including land conversion and land management practices, would lead to a 5.5% increase in river discharge by the 2090s relative to the present level under the A2 scenario, with a very slight increase of 1.0% under the B1 scenario. Our projected increase in river discharge resulting from land use change is consistent with the land-use-induced base flow and streamflow increases in the Mississippi River basin since the 1940s [*Zhang and Schilling*, 2006]. Furthermore, our study is supported by a global modeling analysis that showed a 5.0% increase in river discharge due to land conversion during 1971–2000 [*Rost et al.*, 2008]. However, land use impact on hydrological processes is complicated, which highly depends on land conversion types and associated land management practices. For example, clearing forests for cropland decreases evapotranspiration, thus increases runoff. In contrast, land conversion from grassland to cropland may increase evapotranspiration and decrease runoff [*Frans et al.*, 2013; *Twine et al.*, 2004]. Our analyses show that forest conversion would account for approximately 26% of crop expansion area under the A2 scenario, compared to 6% under the B1 scenario. This partially explains why the land-use-induced river discharge increase under the A2 scenario is much higher than that under the B1 scenario (5.5% versus 1.0%), even though cropland increase in the B1 scenario is one third that of the A2 scenario. Our factorial analyses suggest that land use change would account for 15.4% and 3.4% of the total changes in projected river discharge under the A2 and B1 scenarios, respectively (Figures 2c and 2d). This demonstrates that land use change, including land conversion and land management, would have bigger influences on the hydrological cycle under the high-emission scenarios (A2), which is characterized by self-reliant nations, continuously increasing populations, and regionally oriented economic development. While under the B1 scenario, lower population growth, smaller increases in cropland and urban area, and more eco-friendly lifestyles would result in much less intensive land use change, therefore would not have substantial influences on water resources. The projected increase of river discharge induced by land use (about 5.5%) is lower than the results from a tropical study in Brazil which showed a 25% increase in river discharge, mainly due to crop expansion during 1960–1995 [*Costa et al.*, 2003]. The differences among these findings might be attributed to two factors. First, *Costa et al.* [2003] used a census-based method to estimate changes in river discharge, which incorporated not only land use change but also other environmental factors such as climate change (although precipitation was reported to remain roughly constant during the study period). Second, unlike the MRB, a majority of land conversions that happened in the Brazilian Amazon were from the conversion of forests to cropland, which could substantially

decrease evapotranspiration and therefore greatly enhance river discharge even if precipitation underwent no major change. Furthermore, as one of the most productive agricultural regions worldwide [*Foley et al.*, 2004], land use in the MRB is generally more intensive than other regions.

Our single-factor (E2) simulations of a doubling of atmospheric CO_2 concentration under the A2 scenario project a 22.7% increase in river discharge, compared to the recent 10 years (2000–2009). The factorial analyses suggest that the atmospheric CO_2 concentration would account for 35.8% and 21.9% of the total changes in projected river discharge under the A2 and B1 scenarios, respectively, which are just less than the relative contribution from climate effects (Figures 2c and 2d). We recognize that global projections have estimated only a 6% increase in runoff compared to preindustrial levels due to a doubled CO_2 concentration [*Betts et al.*, 2007], a value that is lower than our simulated increase in runoff (14%) in the MRB under the CO_2, doubling the A2 scenario. In the current DLEM scheme, the effect of atmospheric CO_2 on stomatal conductance is derived from the meta-analysis of *Ainsworth and Long* [2005]. It can generally capture changes in evapotranspiration and streamflow in response to historical atmospheric CO_2 increase [*Liu et al.*, 2013] but may, to some extent, overestimate future river discharge without considering acclimation of plant stomata conductance to CO_2 increase.

In conclusion, our analyses suggest that if emissions would continue like the A2 scenario, the combined effects of human-induced CO_2 elevation (35.8%) and intensive land use change (15.4%) on river discharge would outweigh climate change effect (48.8%) in the MRB (Figure 2). Under the B1 scenario, however, climate change would still be the dominant factor controlling hydrological processes in both magnitude and temporal patterns. These findings are consistent with anthropogenically enhanced water fluxes in the past century reported by *Raymond et al.* [2008].

4. Summary

In this study, the process-based simulations with the DLEM model suggest a substantial increase in Mississippi river discharge throughout the 21st century, attributing not only to hydrological intensification resulting from a warming climate but also to future land use change and CO_2 concentration elevation. Our analyses indicate that climate change would still be a dominant factor controlling hydrological processes under the B1 scenario. Under the high-emission scenario (A2), however, human-induced atmospheric CO_2 increase and land use change would outweigh climate effects in accounting for projected increases in river discharge in the Mississippi River basin. This projection of increased river discharge implies that riverine fluxes of carbon, nutrients, and pesticide from the Mississippi River basin to coastal regions would also increase in the future and thus may influence ocean ecosystems and the state of ocean acidification and hypoxia, leading to a deterioration in ocean water quality [*Durack et al.*, 2012].

This study has explored how changes in multiple environmental factors would affect river discharge and uncertainties associated with climate models, emission scenarios, and process representation in ecosystem modeling. It demonstrates the importance of land use change and atmospheric CO_2 concentrations in projecting future hydrologic processes. To improve model representation of plant physiological responses to CO_2 increases (e.g., stomatal conductance) is needed to better constrain the projected effects of CO_2 increases on hydrological processes. Further efforts are also needed to account for additional environmental factors (e.g., nitrogen deposition, tropospheric ozone pollution, and dam construction) in projecting changes in the hydrological cycle.

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