The impact of climate, CO_2, nitrogen deposition and land use change on simulated contemporary global river flow

Xiaoying Shi,[1] Jiafu Mao,[1] Peter E. Thornton,[1] Forrest M. Hoffman,[2] and Wilfred M. Post[1]

Received 13 January 2011; revised 14 March 2011; accepted 17 March 2011; published 23 April 2011.

[1] We investigated how climate, rising atmospheric CO_2 concentration, increasing anthropogenic nitrogen deposition and land use change influenced continental river flow over the period 1948–2004 using the Community Land Model version 4 (CLM4) with coupled river transfer model (RTM), a global river routing scheme. The model results indicate that the global mean river flow shows significant decreasing trend and climate forcing likely functions as the dominant controller of the downward trend during the study period. Nitrogen deposition and land use change account for about 5% and 2.5% of the decrease in simulated global scale river flow, respectively, while atmospheric CO_2 accounts for an upward trend. However, the relative role of each driving factor is heterogeneous across regions in our simulations. The trend in river flow for the Amazon River basin is primarily explained by CO_2, while land use change accounts for 27.4% of the downward trend in river flow for the Yangtze rive basin. Our simulations suggest that to better understand the trends of river flow, it is not only necessary to take into account the climate, but also to consider atmospheric composition, carbon-nitrogen interaction and land use change, particularly for regional scales. **Citation:** Shi, X., J. Mao, P. E. Thornton, F. M. Hoffman, and W. M. Post (2011), The impact of climate, CO_2, nitrogen deposition and land use change on simulated contemporary global river flow, *Geophys. Res. Lett.*, *38*, L08704, doi:10.1029/2011GL046773.

1. Introduction

[2] Climate change and human activities are expected to change the global hydrological cycle in the coming decades [*Gedney et al.*, 2006; *Labat et al.*, 2004; *Milly et al.*, 2005; *Oki and Kanae*, 2006]. There is a prevailing notion that as climate warming continues there will be an intensification of the hydrological cycle that can lead to more severe storms, floods, and droughts [*Huntington*, 2006; *Tucker and Slingerland*, 1997]. However, the changing hydrological cycle is not only a function of climate; vegetation plays a key role over land. The impact of plants on regulating future hydrology is important and needs to be considered in light of multiple influences on ecosystems, including changes in atmospheric CO_2 concentration and nitrogen limitation [*Felzer et al.*, 2009].

[3] Elevated CO_2 can influence the hydrological cycle in two different ways. On one hand, elevated CO_2 results in reduced stomatal conductance, and less water is lost from leaves to the atmosphere in a high-CO_2 atmosphere [*Field et al.*, 1995] (stomatal closure effect). A previous study [*Gedney et al.*, 2006] has shown that increasing CO_2 concentrations over the period 1960–1994 have reduced evapotanspiration (ET) and increased runoff through the stomatal closure effect *Piao et al.* [2007] and *Krakauer and Fung* [2008] found that climate and land use change play more important roles than the stomatal closure effect in increasing runoff. On the other hand, rising CO_2 can increase photosynthesis. If more primary production is allocated to leaf production, then leaf area index (LAI) may increase, leading to increased ET [*Alkama et al.*, 2010; *Betts et al.*, 2007; *Cramer et al.*, 2001; *Felzer et al.*, 2009] (LAI effect).

[4] The ability of plants to respond to elevated CO_2 may also be controlled by nutrient limitation. For example, plant growth due to CO_2 fertilization may be reduced in nitrogen-limited conditions [*Norby et al.*, 2010], while anthropogenic nitrogen deposition has reduced nitrogen limitation in temperate and boreal forests [*Magnani et al.*, 2007; *Melillo and Steudler*, 1989].

[5] Land use is another factor controlling the water balance of ecosystems and the associated river flow. *Piao et al.* [2007] have reported that land use could play an important role on the global river runoff via a decrease in ET when irrigation is neglected. Over China, deforestation leads on average to increased ET for the 20th century, due to the irrigation of agricultural land replacing forest [*Liu et al.*, 2008]. Over the Tocantins Basin of the Amazonian region, an increase in agricultural land with no precipitation change leads to an increase in river runoff [*Costa et al.*, 2003].

[6] River flow is a temporally lagged, spatial integration of runoff over a river basin. It is a useful indicator of freshwater availability, and can thus be used to indicate likely impacts of climate change and other external forcing (atmospheric CO_2 concentration, nitrogen deposition and land use change) on water resources and flooding. However, most earlier studies of changes in river flow at the global scale have used stand-alone river flow models driven by climate data output from General Circulation Models [*Arnell*, 2003, 1999; *Milly et al.*, 2005; *Nijssen et al.*, 2001a, 2001b]. Only a few studies have used a comprehensive land surface model including a river routing sub-model to investigate the impact of climate change on global river flow [*Dai et al.*, 2009; *Falloon and Betts*, 2006]. Many previous studies focused on the impacts of different driving factors, such as climate change, atmospheric CO_2 concentration, land use change and nitrogen limitation on runoff [*Betts et al.*,

[1]Environmental Science Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

[2]Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

0094-8276/11/2011GL046773

Table 1. Experimental Design

	Driving Factors			
Simulation	Climate	Increasing CO_2	Nitrogen Deposition	Land Use Change
All	yes	yes	yes	yes
CLIM	yes	no	no	no
CO_2 (E1-CLIM)	no	yes	no	no
NDEP(E2-CLIM)	no	no	yes	no
LUC(E3-CLIM)	no	no	no	yes

2007; *Cramer et al.*, 2001; *Felzer et al.*, 2009; *Gedney et al.*, 2006; *Piao et al.*, 2007]. However, globally comprehensive analyses of the impacts of the different driving factors mentioned above on river flow are lacking. In addition, datasets with observed streamflow from farthest downstream gauge stations exist, while there is not directly observed runoff data. Thus, the purpose of the present study is to investigate how climate, combined with atmospheric CO_2, nitrogen deposition and land use change, have modified the regional and global river flow patterns. We use the CLM4 including prognostic carbon and nitrogen cycles and a river transfer model (RTM), to separately quantify the hydrological contributions of the different driving factors. Previous modeling studies on the hydrological cycle in Community Climate System Model (CCSM) used CLM3 without dynamic carbon and nitrogen biogeochemistry [*Dai and Trenberth*, 2002; *Oleson et al.*, 2008; *Qian et al.*, 2007, 2006]. This is the first time that the effects of multiple biogeochemical driving factors on river flow are investigated using the CLM4 model.

2. Model and Experimental Design

2.1. Model Description

[7] The CLM4 is the result of merging the biophysical framework of the CLM 3.5 [*Oleson et al.*, 2008; *Stöckli et al.*, 2008] with the fully prognostic carbon and nitrogen dynamics of the terrestrial biogeochemistry model Biome-BGC (version 4.1.2) [*Thornton and Rosenbloom*, 2005; *Thornton et al.*, 2002]. The resulting model, CLM4, includes

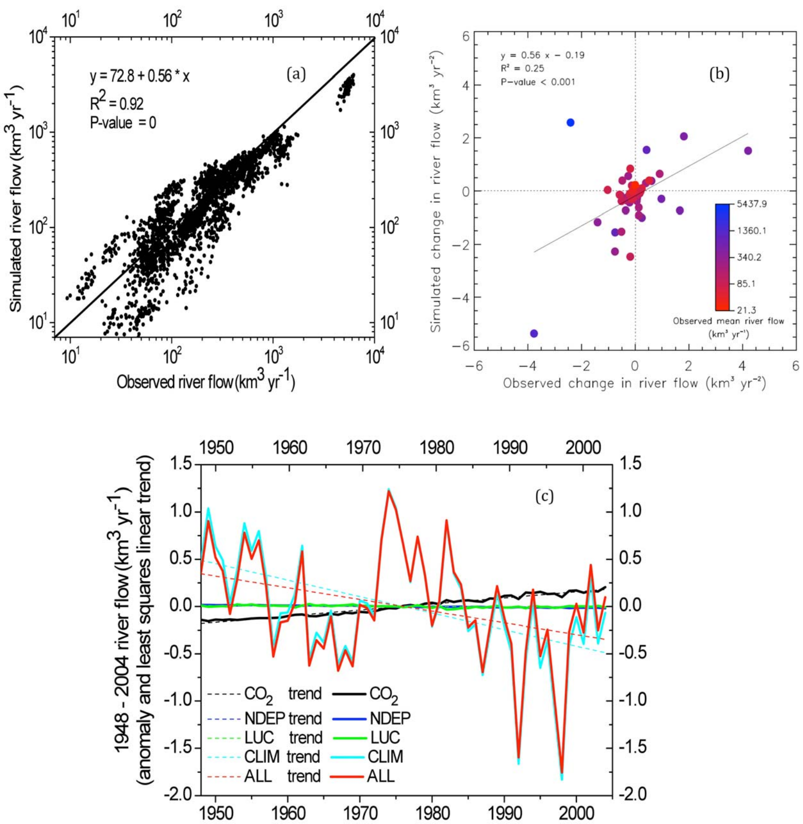

Figure 1. (a) Scatter plot of predicted vs. observed annual river flow over the period 1948–2004 for the world's 50 largest rivers. Annual simulated river flow is from simulation ALL. The solid line is the 1:1 line. The linear regression equation, the square of the correlation coefficient (R^2) between the simulation and observation, and P value are shown. (b) Comparison of predicted vs. observed change in river flow over the period 1948–2004 for the world's 50 largest rivers, where each point represents one river. Change in river flow for each river is evaluated as the linear regression slope of annual flow over the period, from observations and from simulation ALL. Symbol color indicates the observed mean river flow over the period. (c) Time series of model annual anomalies of global averaged river flow ($km^3\ yr^{-1}$) and associated least squares linear trend over the period 1948–2004.

Table 2. Annual Trends From the Global Scale River Flow During 1948–2004 as Shown in Figure 1c

Simulations	Slope b (km^3 yr^{-2})	Standard Error of b (km^3 yr^{-2})	P Value
ALL	−0.0123	0.0044	0.0073
CLIM	−0.0174	0.0044	0.0002
CO_2	0.0064	0.0002	<0.0001
NDEP	−0.0006	0.00002	<0.0001
LUC	−0.0003	0.00009	0.0003

carbon-nitrogen biogeochemistry with prognostic carbon and nitrogen in vegetation, litter, and soil organic matter [*Thornton and Zimmermann*, 2007; *Thornton et al.*, 2009]. The RTM is used for routing surface runoff into river channels, and through the channel network to the oceans. More details about RTM are described by *Oleson et al.* [2010].

2.2. Experimental Design

[8] The CLM4 was used to simulate historical land surface conditions driven by a 57 year (1948–2004) observation-constrained atmospheric forcing dataset [*Qian et al.*, 2006]. The simulation was spun up for 1850 conditions (atmospheric CO_2, nitrogen deposition, and land cover), driven by a repeating 25 year subset (1948–1972) of the meteorological forcing data. The simulations for 1850–1947 used the same repeating 25 year meteorology, and the 1948–2004 meteorology was used in simulation experiments for 1948–2004. Annual land use change and harvest area were derived from the University of New Hampshire version 1 Land-Use History A (LUHa.v1) historical dataset based on that of *Hurtt et al.* [2006]. Effects of rotational wood harvest, conversion of natural vegetation to agriculture or pasture and abandonment of managed lands are included in the land use change term (the spatial distributions of four land use types from *Hurtt et al.* [2006] are given in Figure S1 of the auxiliary material).[1] The details of the atmospheric CO_2 concentration and nitrogen deposition (Figure S2 shows nitrogen deposition spatial distribution of 1948 and 2004, and time series from 1948 to 2004) are described by *Bonan and Levis* [2010].

[9] We carry out 5 simulations and then use single simulations and differences between pairs of simulations to isolate the effects of changing CO_2 concentration, nitrogen deposition and land use change (Table 1). We allow all factors (climate, atmospheric CO_2, nitrogen deposition and land use change) to vary throughout the fully transient simulation (named ALL). To consider the impact of climate on river flow, we use historical climate but hold the other three factors constant at their values for 1850 (named CLIM). In the three remaining simulations we allow climate and one of the three factors to vary while holding the other two components constant at their 1850 values. These three simulations (E1 = climate and CO_2, E2 = climate and nitrogen deposition, E3 = climate and land use change) are compared to experiment CLIM (through differencing) to isolate individual effects. Experiments named CO_2 (E1-CLIM), NDEP (E2-CLIM) and LUC (E3-CLIM) isolate the contributions of increasing atmospheric CO_2 concentration, increasing anthropogenic nitrogen deposition and land use change, respectively.

3. Results and Discussions

[10] We first compare the model against historical river flow for the world's top 50 rivers over the period 1948–2004. Figure 1a compares, on logarithmic scales, the CLM4 simulated annual river flows from simulation ALL with observations from farthest downstream gauges [from *Dai et al.*, 2009]. The simulated and observed river flows are highly correlated (R^2 = 0.92 on linear scale). The large scatter for high values of river flow in Figure 1a reflects the fact that high river flow is more difficult to simulate than low river flow. Figure 1b compares observed and predicted (simulation ALL) trends in annual river flow over the period 1948–2004 for the world's 50 largest rivers. The predicted and observed trends in river flow are significantly correlated, although the simulation captures only a modest fraction of the observed variance (R^2 = 0.25). The comparisons suggest that it is valid to use the CLM4 model simulations to evaluate the mechanisms controlling the river flow change.

[11] Figure 1c shows simulated annual anomalies of global averaged river flow, with the linear trends for the period 1948–2004 summarized in Table 2. River flow from simulations CLIM and ALL shows significant decreasing trends with rates of -0.0174 ± 0.0044 km^3 yr^{-1} and -0.0123 ± 0.0044 km^3 yr^{-1}, respectively (attained significance level p = 0.0002 and 0.0073, respectively). Simulation CO_2 shows an increasing trend with a rate of 0.0064 ± 0.0002 km^3 yr^{-1} ($p < 0.0001$). Nitrogen deposition and land use change have small significant effects on the modeled global-scale river flow, with trends of -0.0006 ± 0.00002 km^3 yr^{-1} and -0.0003 ± 0.00009 km^3 yr^{-1}, respectively ($p<0.0001$). The modeled river flow shows large interannual and decadal variations forced by climate variability, which is consistent with previous studies [*Cluis and Laberge*, 2001; *Dai et al.*, 2004, 2009; *Huntington*, 2006].

[12] Figure 2 shows the spatial distribution of the CLM4 simulated river flow trends (Figures 2a–2e) and their dominant driving factors (Figure 2g), trends in precipitation (Figure 2f) during 1948–2004, and 10 selected river basin regions (Figure 2h). While river flow decrease/increase may be attributed to more than one factor for any given watershed, the one with the largest contribution is defined as the dominant factor for that region. Despite the significant global decrease in river flow for the simulation ALL, there is a pronounced geographical heterogeneity in its trends (Figure 2a), reflecting the spatial patterns of changes in climatic conditions (Figure 2b), chiefly in precipitation (Figure 2f). Significant decreases in river flow are found for large areas of the globe, including Eurasia, Alaska, Canada, western part of Amazon and central South America, Eastern Australia, and central and southern Africa (Figure 2a), where downward trends in annual precipitation are also found (Figure 2f). In contrast, increasing trends in river flow are found for central Europe, some part of Asia, North Africa, most part of United States including Mississippi river basin, central and western Australia, eastern part of Amazon basin and southeastern South America. Similar spatial patterns of river flow trends are also found from CLIM simulation (Figure 2b), also consistent with trends in precipitation (Figure 2f). These results agree with the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL046773.

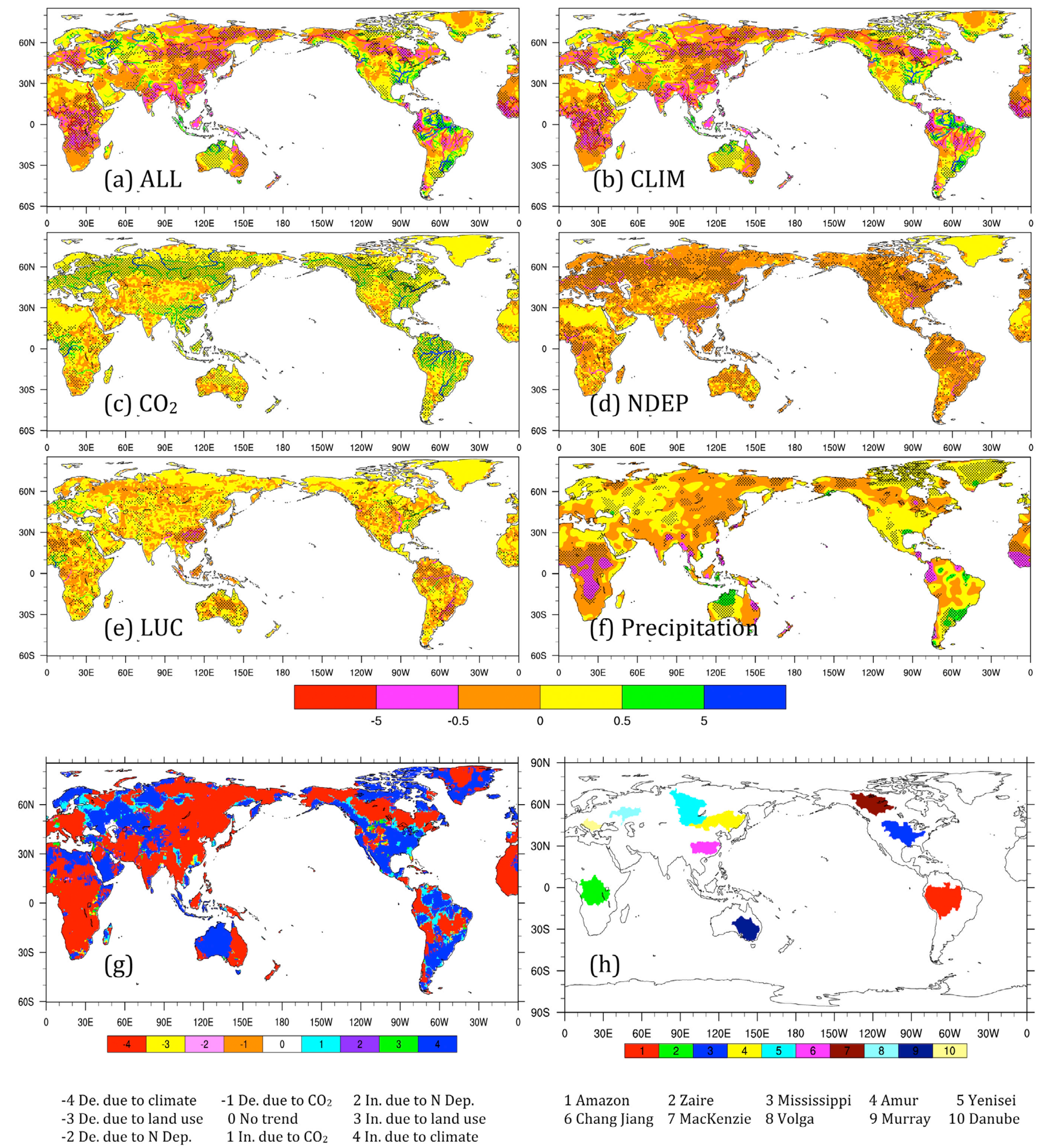

Figure 2. (a-e) Spatial distribution of CLM4 simulated river flow trend (km^3/57yrs), (f) precipitation trend (mm day^{-1}/57yrs), (g) dominant driving factors causing decreasing (De.) or increasing (In.) trend during 1948–2004, and (h) selected 10-river basin regions. Stipples in Figures 2a–2f mean the trend is statistically significant at the 5% level based on 2-sided Student's t test.

conclusions drawn from river flow records. For example, decreased river flow has been reported over many Canadian river basins [*Zhang et al.*, 2001] while increased river flow has been reported over other regions, such as many parts of United States [*Groisman et al.*, 2001; *Lins and Slack*, 1999] and southeastern South America [*Genta et al.*, 1998; *Pasquini and Depetris*, 2007]. Simulated river flow over Siberia region, including Yenisei river basin, shows a decreasing trend during 1948–2004 (Figure 2a and Table 3). This contradicts the upward trend in Yenisei's river flow rates since 1960s reported by *Yang and Ye* [2004]. A mechanism for the observed increase has not been identified by them.

[13] As mentioned above, in response to increasing CO_2, global averaged river flow shows a significant upward trend. Figure 2c also demonstrates that increasing trends in river flow appear in most parts of globe, excluding some part of

Table 3. The Least Squares Linear Trends in Annual Mean River Flow of ALL, CLIM, CO_2, NDEP and LUC Simulations for Globe and 10 River Basin Regions During 1948–2004 (km^3 yr^{-1})

Region	ALL	CLIM	CO_2	NDEP	LUC
Globe	−0.0123	−0.0174	0.0064	−0.0006	−0.0003
Amazon	0.0084	−0.0404	0.0505	−0.0012	−0.0004
Zaire	−0.1258	−0.1343	0.0105	−0.0011	−0.0008
Mississippi	0.0371	0.0313	0.0104	−0.0026	−0.0012
Amur	−0.0490	−0.0554	0.0072	−0.0006	0.0002
Yenisei	−0.0239	−0.0315	0.0086	−0.0005	−0.0003
Chang Jiang	−0.0742	−0.0764	0.0274	−0.0035	−0.0203
Mackenzie	−0.0145	−0.0224	0.0083	−0.0003	0.0000
Volga	0.0416	0.0319	0.0108	−0.0019	0.0014
Murray	−0.0013	−0.0015	0.0002	0.0000	0.0000
Danube	−0.0675	−0.0765	0.0105	−0.0042	0.0046

Eurasia, southwestern United States, South Africa and some parts of eastern central Africa, some areas of western and southern Australia. Similar patterns are found for simulated river runoff (Figure S3c). LAI shows an upward trend in most parts of globe (Figure S3a), while transpiration shows mostly downward trends (Figure S3e). This result is similar to previous conclusions [*Alkama et al.*, 2010; *Betts et al.*, 2007; *Cramer et al.*, 2001; *Felzer et al.*, 2009].

[14] Increasing anthropogenic nitrogen deposition caused decreasing trends in river flow over most regions, except north of Africa and some parts of Eurasia, and Greenland (Figure 2d). Meanwhile, anthropogenic nitrogen depositions of Southeast of China, West Europe, Southeast of United States and Central Africa have increased during the study period (Figures S2a and S2b) where river flows have decreased significantly. Our NDEP simulation suggests that increasing anthropogenic nitrogen deposition can alleviate the nitrogen limitation effect on photosynthesis resulting in increasing LAI (Figure S3b) and transpiration (Figure S3f), leading to less runoff (Figure S3d) and decreasing river flow (Figure 2d). Previous studies also have reported that anthropogenic nitrogen deposition has relieved nitrogen limitation in temperate and boreal forests [*Magnani et al.*, 2007; *Melillo and Steudler*, 1989]. A recent study shows that consideration of nitrogen limitation and ozone damage on photosynthesis increases future runoff by 6–11% [*Felzer et al.*, 2009], however that study did not explicitly model nitrogen deposition.

[15] The overall impact of land use change on global scale river flow trend is the smallest of the factors considered here. However, river flow distribution in the simulation LUC shows regionally heterogeneous trends. Pronounced decreases are observed in North Africa, southern China, Amazonian river basin region and north central part of Australia (Figure 2e), where increasing ET (results not shown) due to land use change results in less river flow. Over Southern China, increases in crop and pasture lands (Figures S1e-S1h) induce increasing ET, and result in less river flow. Over the Amazonian river basin and North Africa, the decreasing river flow might arise from increasing ET caused by conversion from primary to secondary forest (Figures S1a-S1d). Studying the effect of land use change on Chinese region water resource, *Liu et al.* [2008] also reported that deforestation leads to an average increased ET for the 20th century, due to the irrigation of the agricultural land replacing forest. Our simulations do not include the influence of irrigation, but land use conversions in this region still lead to increased ET.

[16] Figure 2g shows that climate forcing is the primary driving factor in river flow over most parts of globe, but CO_2 is the main cause over some parts of northern Europe and United States, and Amazon River basin region. Land use change plays an important role in a few parts of globe, such as southeastern China, and northwestern United Stated.

[17] To quantify the effect of different driving factors on regional scale river flow change trends, we selected 10 river basin regions from different continents (Figure 2h) and calculated their river flow trends for all simulations, summarized in Table 3. The river flow trends of most river basin regions are negative, except for Amazon, Mississippi and Volga river basin regions. Climate forcing is the primary driving factor in global scale simulated river flow, and then atmospheric CO_2 concentration, followed by nitrogen deposition and land use change accounting for about 5% and 2.5% of the decreasing trend, respectively. However, the same order of factors does not apply for regional scale simulated river flow (Figure 2g and Table 3). For example, atmospheric CO_2 concentration is the main cause of simulated river flow change for Amazon River basin region, and land use change plays a more important role than nitrogen deposition for simulated river flow trend in Yangzte river valley region (land use change and nitrogen deposition account for about 27.4% and 4.7%, respectively).

4. Summary

[18] In this study, results from process-based simulations of global river flow using the CLM4 model suggest that significant decrease in global averaged river flow during 1948–2004 is mainly a consequence of climate forcing. In addition, nitrogen deposition and land use change make minor contributions to this decreasing trend. In contrast, CO_2 causes an increasing trend of global scale river flow. Our result is consistent with the conclusion reported by *Dai et al.* [2009], who qualitatively showed that direct human influence on annual river flow is likely small compared with climatic forcing during 1948–2004 for most of the world's major rivers. Moreover, our results also showed that the relative role of different driving factors is not constant across the globe. On the basis of our model results, not only the roles of climate forcing but also vegetation-hydrology interactions and land use change should be considered when projecting future changes in hydrologic processes.

[19] The river routing scheme currently used in CLM4 does not explicitly account for reservoir operation. This may not be a serious problem for analysis such as ours at the annual time scale, since the influence of reservoirs on annual river flow is likely small [*Dai et al.*, 2009]. Our simulations do not consider ozone pollution, or changes in aerosols or solar irradiance, all of which might influence regional and global trends. Further studies are still needed to quantify the effects of these additional factors on river flow.

[20] **Acknowledgments.** This study was supported by the U.S. Department of Energy, Office of Science, Biological and Environmental Research. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

[21] The Editor thanks anonymous reviewers for their assistance in evaluating this paper.

References

Alkama, R., M. Kageyama, and G. Ramstein (2010), Relative contributions of climate change, stomatal closure, and leaf area index changes to 20th and 21st century runoff change: A modelling approach using the Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) land surface model, *J. Geophys. Res.*, *115*, D17112, doi:10.1029/2009JD013408.

Arnell, N. (1999), Climate change and global water resources, *Global Environ. Change*, *9*, S31–S49, doi:10.1016/S0959-3780(99)00017-5.

Arnell, N. (2003), Effects of IPCC SRES* emissions scenarios on river runoff: A global perspective, *Hydrol. Earth Syst. Sci.*, *7*(5), 619–641, doi:10.5194/hess-7-619-2003.

Betts, R., O. Boucher, M. Collins, P. Cox, P. Falloon, N. Gedney, D. Hemming, C. Huntingford, C. Jones, and D. Sexton (2007), Projected increase in continental runoff due to plant responses to increasing carbon dioxide, *Nature*, *448*(7157), 1037–1041, doi:10.1038/nature06045.

Bonan, G., and S. Levis (2010), Quantifying carbon-nitrogen feedbacks in the Community Land Model (CLM4), *Geophys. Res. Lett.*, *37*(7), L07401, doi:10.1029/2010GL042430.

Cluis, D., and C. Laberge (2001), Climate change and trend detection in selected rivers within the Asia-Pacific region, *Water Int.*, *26*(3), 411–424, doi:10.1080/02508060108686933.

Costa, M., A. Botta, and J. Cardille (2003), Effects of large-scale changes in land cover on the discharge of the Tocantins River, southeastern Amazonia, *J. Hydrol. Amsterdam*, *283*(1–4), 206–217, doi:10.1016/S0022-1694(03)00267-1.

Cramer, W., A. Bondeau, F. Woodward, I. Prentice, R. Betts, V. Brovkin, P. Cox, V. Fisher, J. Foley, and A. Friend (2001), Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models, *Global Change Biol.*, *7*(4), 357–373, doi:10.1046/j.1365-2486.2001.00383.x.

Dai, A., and K. Trenberth (2002), Estimates of freshwater discharge from continents: Latitudinal and seasonal variations, *J. Hydrometeorol.*, *3*(6), 660–687, doi:10.1175/1525-7541(2002)003<0660:EOFDFC>2.0.CO;2.

Dai, A., K. Trenberth, and T. Qian (2004), A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, *5*(6), 1117–1130, doi:10.1175/JHM-386.1.

Dai, A., T. Qian, K. Trenberth, and J. Milliman (2009), Changes in continental freshwater discharge from 1948 to 2004, *J. Clim.*, *22*(10), 2773–2792, doi:10.1175/2008JCLI2592.1.

Falloon, P., and R. Betts (2006), The impact of climate change on global river flow in HadGEM1 simulations, *Atmos. Sci. Lett.*, *7*(3), 62–68, doi:10.1002/asl.133.

Felzer, B. S., T. W. Cronin, J. M. Melillo, D. W. Kicklighter, and C. A. Schlosser (2009), Importance of carbon-nitrogen interactions and ozone on ecosystem hydrology during the 21st century, *J. Geophys. Res.*, *114*, G01020, doi:10.1029/2008JG000826.

Field, C., R. Jackson, and H. Mooney (1995), Stomatal responses to increased CO_2: Implications from the plant to the global scale, *Plant Cell Environ.*, *18*(10), 1214–1225, doi:10.1111/j.1365-3040.1995.tb00630.x.

Gedney, N., P. Cox, R. Betts, O. Boucher, C. Huntingford, and P. Stott (2006), Detection of a direct carbon dioxide effect in continental river runoff records, *Nature*, *439*(7078), 835–838, doi:10.1038/nature04504.

Genta, J., G. Perez-Iribarren, and C. Mechoso (1998), A recent increasing trend in the streamflow of rivers in southeastern South America, *J. Clim.*, *11*(11), 2858–2862, doi:10.1175/1520-0442(1998)011<2858:ARITIT>2.0.CO;2.

Groisman, P., R. Knight, and T. Karl (2001), Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century, *Bull. Am. Meteorol. Soc.*, *82*(2), 219–246, doi:10.1175/1520-0477(2001)082<0219:HPAHSI>2.3.CO;2.

Huntington, T. (2006), Evidence for intensification of the global water cycle: Review and synthesis, *J. Hydrol.*, *319*(1–4), 83–95, doi:10.1016/j.jhydrol.2005.07.003.

Hurtt, G., S. Frolking, M. Fearon, B. Moore, E. Shevliakova, S. Malyshev, S. Pacala, and R. Houghton (2006), The underpinnings of land use history: Three centuries of global gridded land use transitions, wood harvest activity, and resulting secondary lands, *Global Change Biol.*, *12*(7), 1208–1229, doi:10.1111/j.1365-2486.2006.01150.x.

Krakauer, N. Y., and I. Fung (2008), Mapping and attribution of change in streamflow in the coterminous United States, *Hydrol. Earth Syst. Sci.*, *12*(4), 1111–1120, doi:10.5194/hess-12-1111-2008.

Labat, D., Y. Godderis, J. Probst, and J. Guyot (2004), Evidence for global runoff increase related to climate warming, *Adv. Water Resour.*, *27*(6), 631–642, doi:10.1016/j.advwatres.2004.02.020.

Lins, H., and J. Slack (1999), Streamflow trends in the United States, *Geophys. Res. Lett.*, *26*(2), 227–230, doi:10.1029/1998GL900291.

Liu, M., H. Tian, G. Chen, W. Ren, C. Zhang, and J. Liu (2008), Effects of land-use and land-cover change on evapotranspiration and water yield in China during 1900–2000, *J. Am. Water Resour. Assoc.*, *44*(5), 1193–1207, doi:10.1111/j.1752-1688.2008.00243.x.

Magnani, F., M. Mencuccini, M. Borghetti, P. Berbigier, F. Berninger, S. Delzon, A. Grelle, P. Hari, P. Jarvis, and P. Kolari (2007), The human footprint in the carbon cycle of temperate and boreal forests, *Nature*, *447*(7146), 849–851, doi:10.1038/nature05847.

Melillo, J. M., and P. A. Steudler (1989), The effect of nitrogen fertilization on the COS and CS2 emissions from temperature forest soils, *J. Atmos. Chem.*, *9*, 411–417, doi:10.1007/BF00114753.

Milly, P., K. Dunne, and A. Vecchia (2005), Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, *438*(7066), 347–350, doi:10.1038/nature04312.

Nijssen, B., G. O'Donnell, A. Hamlet, and D. Lettenmaier (2001a), Hydrologic sensitivity of global rivers to climate change, *Clim. Change*, *50*(1–2), 143–175, doi:10.1023/A:1010616428763.

Nijssen, B., G. M. O'Donnell, D. P. Lettenmaier, D. Lohmann, and E. F. Wood (2001b), Predicting the discharge of global rivers, *J. Clim.*, *14*(15), 3307–3323, doi:10.1175/1520-0442(2001)014<3307:PTDOGR>2.0.CO;2.

Norby, R. J., J. M. Warren, C. M. Iversen, B. E. Medlyn, and R. E. McMurtrie (2010), CO_2 enhancement of forest productivity constrained by limited nitrogen availability, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(45), 19,368–19,373, doi:10.1073/pnas.1006463107.

Oki, T., and S. Kanae (2006), Global hydrological cycles and world water resources, *Science*, *313*(5790), 1068–1072, doi:10.1126/science.1128845.

Oleson, K., G. Niu, Z. Yang, D. Lawrence, P. Thornton, P. Lawrence, R. Stöckli, R. Dickinson, G. Bonan, and S. Levis (2008), Improvements to the Community Land Model and their impact on the hydrological cycle, *J. Geophys. Res.*, *113*, G01021, doi:10.1029/2007JG000563.

Oleson, K., D. Lawrence, B. Gordon, M. Flanner, E. Kluzek, J. Peter, S. Levis, S. Swenson, E. Thornton, and J. Feddema (2010), Technical description of version 4.0 of the Community Land Model (CLM), *NCAR Tech. Note NCAR/TN-478+STR*, Natl. Cent. for Atmos. Res., Boulder, Colo.

Pasquini, A., and P. Depetris (2007), Discharge trends and flow dynamics of South American rivers draining the southern Atlantic seaboard: An overview, *J. Hydrol.*, *333*(2–4), 385–399, doi:10.1016/j.jhydrol.2006.09.005.

Piao, S., P. Friedlingstein, P. Ciais, N. de Noblet-Ducoudré, D. Labat, and S. Zaehle (2007), Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(39), 15,242–14,247, doi:10.1073/pnas.0707213104.

Qian, T., A. Dai, K. E. Trenberth, and K. W. Oleson (2006), Simulation of global land surface conditions from 1948 to 2004. Part I: Forcing data and evaluations, *J. Hydrometeorol.*, *7*(5), 953–975, doi:10.1175/JHM540.1.

Qian, T., A. Dai, and K. E. Trenberth (2007), Hydroclimatic trends in the Mississippi River basin from 1948 to 2004, *J. Clim.*, *20*(18), 4599–4614, doi:10.1175/JCLI4262.1.

Stöckli, R., D. Lawrence, G. Niu, K. Oleson, P. Thornton, Z. Yang, G. Bonan, A. Denning, and S. Running (2008), Use of FLUXNET in the Community Land Model development, *J. Geophys. Res.*, *113*, G01025, doi:10.1029/2007JG000562.

Thornton, P., and N. Rosenbloom (2005), Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model, *Ecol. Modell.*, *189*(1-2), 25–48, doi:10.1016/j.ecolmodel.2005.04.008.

Thornton, P., and N. Zimmermann (2007), An improved canopy integration scheme for a land surface model with prognostic canopy structure, *J. Clim.*, *20*(15), 3902–3923, doi:10.1175/JCLI4222.1.

Thornton, P., B. Law, H. Gholz, K. Clark, E. Falge, D. Ellsworth, A. Goldstein, R. Monson, D. Hollinger, and M. Falk (2002), Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests, *Agric. For. Meteorol.*, *113*(1–4), 185–222, doi:10.1016/S0168-1923(02)00108-9.

Thornton, P., S. C. Doney, K. Lindsay, J. K. Moore, N. Mahowald, J. T. Randerson, I. Fung, J. F. Lamarque, J. J. Feddema, and Y. H. Lee (2009), Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: Results from an atmosphere-ocean general circulation model, *Biogeosciences*, *6*(10), 2099–2120, doi:10.5194/bg-6-2099-2009.

Tucker, G., and R. Slingerland (1997), Drainage basin responses to climate change, *Water Resour. Res.*, *33*(8), 2031–2047, doi:10.1029/97WR00409.

Yang, D., and B. Ye (2004), Streamflow changes over Siberian Yenisei River basin, *J. Hydrol.*, *296*(1–4), 59–80, doi:10.1016/j.jhydrol.2004.03.017.

Zhang, X., K. Harvey, W. Hogg, and T. Yuzyk (2001), Trends in Canadian streamflow, *Water Resour. Res.*, *37*(4), 987–998, doi:10.1029/2000WR900357.

F. M. Hoffman, Computer Science and Mathematics Division, Oak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37831, USA.

J. Mao, W. M. Post, X. Shi, and P. E. Thornton, Environmental Science Division, Oak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37831, USA. (shix@ornl.gov)