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Effects of Nitrogen Limitation on Hydrological Processes in CLM4-CN

Eungul Lee*† and Benjamin S. Felzer*

Abstract

The role of nitrogen limitation on photosynthesis downregulation and stomatal conductance has a significant influence on evapotranspiration and runoff. In the current Community Land Model with coupled Carbon and Nitrogen cycles (CLM4-CN), however, the carbon and water coupling in stomata is not linked to nitrogen limitation. We modify the incomplete linkages between carbon, nitrogen, and water, and examine how nitrogen limitation affects hydrological processes in CLM4-CN. In addition, we evaluate if the modification can improve the simulation of carbon and water fluxes. Applying the effects of nitrogen limitation on stomatal conductance significantly decreases leaf photosynthesis. It leads to a reduction in canopy transpiration, thereby increasing total runoff, mainly due to increasing subsurface runoff. More available soil water for vegetation from the reduced transpiration helps increase gross primary productivity (GPP) in the relatively moisture-limited regions of grassland/steppe and savanna. But, in the tropics and boreal forest regions, changes in soil water by nitrogen limitation are insignificant, and GPP decreases directly by down-regulated leaf photosynthesis. Decreasing canopy transpiration and increasing runoff from nitrogen limitation improve simulating latent heat flux and runoff by reducing high biases for latent heat flux in the tropics and low biases for runoff in the tropics and northern high-latitudes. In addition, the CLM4-CN with leaf-level nitrogen limitation reduces high model biases in tropical GPP. Thus, nitrogen limitation on the leaf-level significantly affects hydrological processes in CLM4-CN and improves the simulation of carbon and water fluxes.

Contents

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1. INTRODUCTION

In order to correctly estimate water demand and supplies, it is important to consider the effects of vegetation on the hydrological cycle. Carbon and water are coupled through the leaf's stomata, which allows CO_2 uptake from the atmosphere through photosynthesis and water to exit through transpiration (Ball *et al.*, 1987; Collatz *et al.*, 1991) as shown in **Figure 1**. This carbon and water coupling can be explained by the Ball-Berry conductance model (Ball *et al.*, 1987). In this model, stomatal conductance changes directly with CO_2 assimilation rate scaled by relative humidity, and inversely by the CO_2 concentration at the leaf surface. In this coupling, two different feedbacks are evident. First, elevated CO_2 increases CO_2 concentration at the leaf surface, which is inversely proportional to stomatal conductance ("negative coupling"). On the other hand, elevated CO_2 increases internal leaf CO_2 through CO_2 assimilation, which is proportional to photosynthetic rate and thereby gross primary productivity (GPP) through CO_2 fertilization ("positive coupling"). So, stomatal conductance is proportional to atmospheric CO_2 through positive coupling, but it is inversely proportional to atmospheric CO_2 through negative coupling. Photosynthesis and transpiration codepend via stomatal conductance, and it shows the critical importance of ecophysiology and biogeochemistry for surface physics (Bonan *et al.*, 2011).

Nitrogen limitation is another important component in the coupling between carbon and water, and can affect the positive coupling. Nitrogen is the most limiting nutrient to net primary productivity (NPP) in mid-high latitudes (Vitousek and Howarth, 1991). Nitrogen limitation diminishes CO_2 fertilization on terrestrial plant productivity in unmanaged ecosystems (Langley and Megonigal, 2010). For example, NPP in northern and temperate ecosystems is limited by the availability of inorganic nitrogen (e.g., McGuire *et al*., 1992). In terrestrial ecosystem simulations, Felzer *et al*. (2009, 2011) show that accounting for how climate warming and elevated CO_2 affect nitrogen limitation can have a significant effect on runoff through these carbon-water linkages in the eastern and western U.S. Therefore, nitrogen limitation can play an important role in the carbon and water coupling as it can reduce photosynthetic rates (e.g., Sokolov *et al*., 2008; Thornton *et al*., 2009; Bonan and Levis, 2010). By reducing photosynthetic rates, nitrogen limitation can diminish the carbon-water positive coupling and reduce stomatal conductance. This carbon-nitrogen-water coupling leads to a change in canopy transpiration, and thereby runoff. In addition, changing transpiration affects photosynthesis through water stress. We could consider other components such as relative humidity and temperature in this coupling, but in this study we focus on nitrogen limitation effects in the carbon-nitrogen-water coupling through leaf's stomata.

In order to consider the role of nitrogen cycling in the coupling between carbon and water, we use the Community Land Model with coupled Carbon and Nitrogen cycles (CLM-CN). Carbon-nitrogen cycle coupling in CLM-CN reduces the simulated global terrestrial carbon uptake response to increasing atmospheric CO_2 concentration by 74%, relative to the carbon-only CLM model (Thornton *et al*., 2007). However, the simulated global GPP (~163 PgC/yr) in the latest version of CLM-CN is still higher than observational estimates (~123 PgC/yr; Beer *et al*., 2010) due to high bias in the tropics (Lawrence *et al*., 2011). More importantly, the carbon and nitrogen coupling is not linked to leaf's stomata, and thus there are missing linkages between leaf-level photosynthesis, canopy transpiration, and hydrological processes in terms of nitrogen limitation in the current CLM-CN. We explain more about these feedbacks in detail in Section 2.1.1. In this study, we examine the effects of nitrogen limitation on carbon-nitrogen-water coupling in leaf's stomata and thereby hydrological processes using the version 4 of CLM-CN (CLM4-CN). In addition, we evaluate model outputs from nitrogen limitation experiments using observational datasets for carbon and water fluxes.

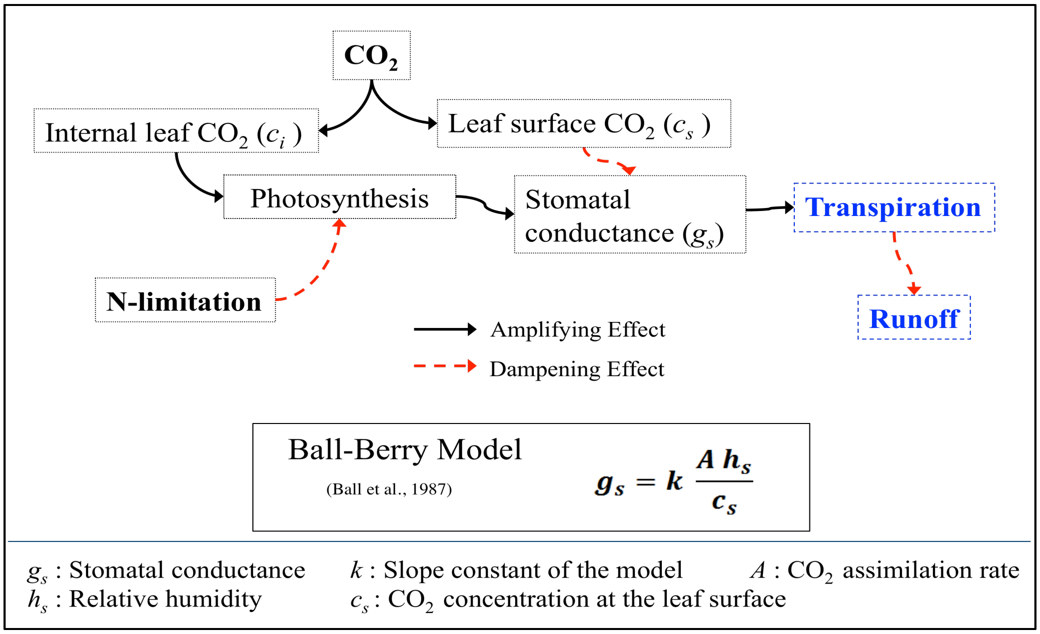

Figure 1. Carbon-Nitrogen-Water coupling through leaf's stomata.

2. METHODS AND DATA

2.1 Model Description and Experiments

CLM4-CN is the result of merging the biophysical framework of CLM4 (Oleson *et al*., 2010; Lawrence *et al*., 2011) with the fully prognostic carbon and nitrogen dynamics of the terrestrial biogeochemistry model, Biome-BGC version 4.1.2 (Thornton and Rosenbloom, 2005). CLM4 incorporates several significant scientific advances over CLM3, including revised soil hydrology and snow processes, organic and deep soils, and the ability to model transient land cover change (Oleson *et al*., 2010). In addition, improvements are made to the way the offline forcing data (i.e. observed meteorological forcing) are applied across the diurnal cycle and to the partitioning of solar radiation into direct versus diffuse radiation (Lawrence *et al*., 2011). One of the major new capabilities in the model, particularly important for this study, is a representation of nitrogen-limiting effects on the carbon cycle. CLM4-CN is fully prognostic with respect to all carbon and nitrogen state variables in the vegetation, litter, and soil organic matter, and retains all prognostic quantities for water and energy in the vegetation-snow-soil column from CLM4 (Thornton *et al*., 2007). Detailed descriptions for the biogeochemical components of CLM4-CN are in Thornton *et al*. (2007). However, the nitrogen limiting effect is not linked to the hydrological processes through stomatal conductance as explained in the following section.

2.1.1 Nitrogen Limitation (Downregulation) Approach

In the current CLM4-CN, canopy-level photosynthesis (or GPP) is derived by summing the sunlit and shaded leaf-level rates multiplied by the sunlit and shaded leaf area indices, with potential reductions due to limited availability of mineral nitrogen (Oleson *et al*., 2010). However, stomatal resistance (inverse of stomatal conductance) is not linked to the down-regulated photosynthesis by nitrogen limitation. For example, the photosynthesis used to control stomatal conductance is calculated from the stomata subroutine within the canopy fluxes module. Then, the leaf-level photosynthesis is used to calculate GPP, and GPP is scaled by a nitrogen limitation factor in the carbon and nitrogen allocation module. So, the photosynthesis used to control stomatal conductance is not affected by nitrogen limitation. It could result in missing feedbacks between leaf-level photosynthesis, transpiration, and hydrological processes in terms of nitrogen limitation in the current CLM4-CN.

In order to fix this bug, we scale the photosynthesis in the stomata subroutine by the nitrogen limitation factor for GPP in the carbon and nitrogen allocation module from the previous time step. From the downregulation approach, leaf-level photosynthesis is scaled by the nitrogen limitation factor, and then stomatal conductance is changed by the scaled photosynthesis through the Ball-Berry function. Therefore, nitrogen limitation may affect transpiration in plants and resulting runoff.

2.1.2 Experimental Design

We perform equilibrium and transient experiments with the Community Earth System Model 1.0.1 (CESM 1.0.1) using CLM4-CN. We use stand-alone CLM4 with observed meteorological forcing from 1948 to 2004 and transient CN, land-use, aerosol and nitrogen deposition, and CO_2 concentration from 1850 to 2004. To get initial conditions, we run stand-alone CLM4 for 700 simulation years with a repeating 25-year (1948 to 1972) meteorological forcing and CN, land-use, aerosol and nitrogen deposition, and a CO_2 level for 1850 conditions using a reference case created by the NCAR bluefire machine. From the equilibrium run for the *control*, we save the last restart file and use it as initial conditions for the equilibrium simulations for the nitrogen limitation experiment (*downregulation*) for 100 years. The equilibrium runs for the *control* and *downregulation* provide initial conditions for transient simulations of the *control* and *downregulation*, respectively. Transient simulations for 1850-1972, followed by equilibrium runs, use transient CN, land-use, aerosol and nitrogen deposition, and CO_2 concentration during 1850-1972, but with a repeating 25-year (1948-1972) meteorological forcing. The simulations for 1850-1972 provide initial conditions for 1973 to the subsequent experiments from 1973 to 2004. The simulations for 1973-2004 use all transient components during 1973-2004 with a transient meteorological forcing. To compare the *downregulation* with the *control* runs, we use 30-year outputs from the 1973-2004 transient experiments, throwing out the first 2 years from each simulation. Experimental designs for equilibrium and transient simulations are shown in **Figure 2**.

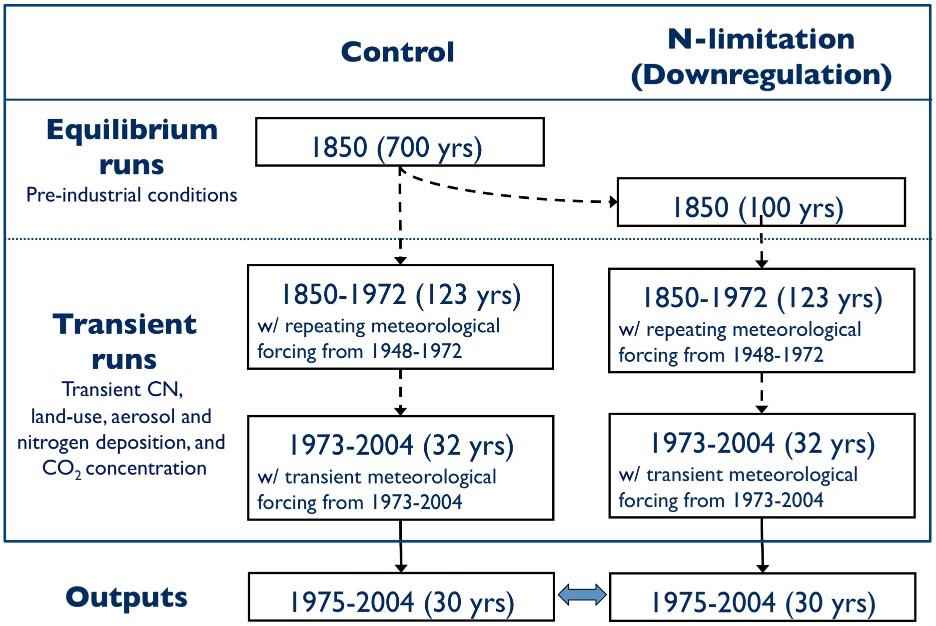

Figure 2. Experimental designs for equilibrium and transient simulations.

2.2 Observational Datasets for Evaluation

As newer observations of carbon and water fluxes become available, it is increasingly important to validate biogeochemical models to improve future projections of atmospheric CO_2 concentrations. Improved validation may require changes to existing model parameterizations, which affect model projections of future carbon and water fluxes. As discussed in the previous section, the effects of nitrogen limitation on leaf photosynthesis are not considered in the current version of CLM4-CN when determining transpiration. This incomplete linkage between carbon-nitrogen-water could affect how well the model output agrees with observations. For example, CLM4 simulates high rates of leaf photosynthesis compared with other photosynthesis models (Chen *et al*., 2011), and the model overestimates carbon uptake due to photosynthesis compared with data-driven estimates and other models, with a particular high bias in the tropics (Beer *et al*., 2010). Also, CLM4-CN produces a high bias for evapotranspiration and a low bias for runoff (Lawrence *et al*., 2011). In evaluations of model outputs, we address how model biases in carbon and water fluxes (evapotranspiration, runoff, and GPP) may result from current model assumptions about the effect of nitrogen limitation on transpiration in CLM4-CN.

In order to evaluate the CLM4-CN *control* and *downregulation* runs, we use gridded observational carbon and water flux data from FLUXNET-MTE (Jung *et al*., 2009, 2011). FLUXNET-MTE is FLUXNET observations of carbon dioxide, water and energy fluxes upscaled to the global scale using the machine learning technique, Model Tree Ensembles

(MTE). MTE method is used to predict site level GPP, terrestrial ecosystem respiration, net ecosystem exchange, latent and sensible heat based on remote sensing data, climate and meteorological data, and information on land use (Jung *et al*., 2011). Jung *et al*. (2011) applied the trained MTEs to generate global flux fields at a 0.5° by 0.5° spatial resolution, covering the globe except for Antarctica, with a monthly temporal resolution from 1982-2008. In addition, we use surface and subsurface runoff data from the Global Soil Wetness Project 2 (GSWP-2) (Dirmeyer *et al*., 2006). GSWP-2 is the multi-model analysis of land surface state variables and fluxes that combines the simulations of more than a dozen different global land surface models. The surface fluxes output data from GSWP-2 have been used as the best estimate of "truth" in numerous global and regional climate-modeling studies (Boone *et al*., 2010). The GSWP-2 product is available globally over land on a regular 1° by 1° grid for a 10-year period from January 1986 through December 1995. For the comparisons with CLM4-CN outputs, we upscale FLUXNET-MTE and GSWP-2 data sets spatially to match the 1.9° by 2.5° (longitude by latitude) grid for the model.

3. RESULTS

3.1 Effects of Leaf-Level Nitrogen Limitation on Hydrological Processes

For the comparisons between *downregulation* and *control* runs, we examine the time series of globally (60°S-90°N) averaged annual mean, spatial percentage-changes, and spatial differences using 30-year (1975-2004) model outputs. For spatial differences, a student *t*-test is conducted to quantify the statistical significance of the difference of means. We use the *t* statistic for unequal population variances, because the *F* tests for the variances of the two samples show significant differences at the 90% in some regions over the globe. Statistically insignificant regions are masked out and significant regions at the 95% level are shown in the figures for spatial differences.

Leaf photosynthesis, which is the sum of sunlit and shaded leaf photosynthesis, increases in both the *control* and *downregulation* runs with increasing transient CO_2 concentration during 1975-2004 (**Figure 3**a). On the other hand, after scaling leaf photosynthesis by a nitrogen limitation factor, globally averaged annual mean leaf photosynthesis is down-regulated by 18.3%. In the spatial patterns of percentage changes, leaf photosynthesis decreases by 10% in the tropics, 20% in the mid-latitudes, and 30-40% in the northern high-latitudes due to nitrogen limitation (Figure 3b). Figure 3c shows the spatial differences between the two runs after masking insignificant regions out. Leaf photosynthesis significantly decreases over the most of vegetated regions across the globe in the *downregulation* run. Larger reductions in photosynthesis are simulated over glassland/steppe in Europe and North America and savanna in South America and Africa. So, the photosynthesis used to control stomatal conductance is lower in the *downregulation* run. We next examine how the down-regulated photosynthesis affects hydrological processes.

The use of down-regulated photosynthesis decreases stomatal conductance and then decreases canopy transpiration as illustrated in the time series, percentage changes, and spatial differences of canopy transpiration (**Figure 4**). During 1975-2004, globally averaged annual mean canopy transpiration decreases by 9.2% with decreases of 10% in the tropics and mid-latitudes and 30-40% in the northern high-latitudes (Figures 4a and b). Statistically significant differences occur in the tropical regions, northern and eastern North America, Europe, Russia, and South China (Figure 4c). The results suggest that down-regulated photosynthesis decreases transpiration by lowering stomatal conductance. Spatial patterns of decreasing total evapotranspiration, which is sum of canopy transpiration, canopy evaporation, and ground evaporation, are consistent with those of decreasing canopy transpiration in the *downregulation* experiment (not shown here).

Reducing canopy transpiration can lead to increasing runoff over vegetated regions. Globally, total liquid runoff increases by 11.9%, and regionally it significantly increases in tropical savanna and mid-latitude grassland/steppes regions by more than 40% in the *downregulation* run (**Figures 5**a, b and c). Next, we examine surface and subsurface runoff, respectively. There is an increase in both surface and subsurface runoff in the *downregulation* run (**Figure 6**a). However, surface runoff increases (4.9%) are not as large as increases in subsurface runoff (18.4%). Spatial differences of subsurface runoff between the two experiments are more consistent with those of total runoff (Figure 6b). So, increasing runoff is mainly due to increasing subsurface runoff by lower canopy transpiration in the *downregulation* run, which means lower transpiration requires less water from the rooting depths.

More available soil water due to decreasing plant transpiration is simulated in the *downregulation* run, with a global increase of 2.1% (**Figure 7**a). Statistically significant increases of more than 5% are shown in grassland/stepps and savanna in the *downregulation* run (Figures 7b and c). More soil water reduces water stress and can lead to more favorable conditions for terrestrial plant productivity.

Time series of globally averaged annual mean of GPP are increasing during 1975-2004, which is consistent with increasing leaf photosynthesis during the same period (**Figure 8**a). However, GPP in the *downregulation* run increases by 2.1% globally, which is different from decreasing leaf photosynthesis. Also, the spatial distributions of GPP differences between the *downregulation* and *control* runs are not consistent with those of leaf photosynthesis (Figure 8b). For example, GPP significantly decreases in tropical and boreal forests, but it significantly increases in grassland/steppe and savanna regions. Increasing GPP over grassland/steppe and savanna regions leads to increasing GPP in the globally averaged annual mean from the *downregulation* run. Changes in soil water as shown in Figure 7c could explain the spatially different changes in GPP. In the *downregulation* run, soil water significantly increases over grassland/steppe and savanna regions. So, increasing soil water in the relatively moisture-limited regions decreases water stress and leads to an increase in GPP. In addition, more soil water from reducing evapotranspiration increases nitrogen mineralization and reduces nitrogen limitation (Felzer *et al*., 2011). On the other hand, changes in soil water in tropical rainforest and boreal forest regions are insignificant (Figure 7c), and thus decreasing leaf photosynthesis from nitrogen limitation directly decreases GPP in the relatively moist regions.

In CLM4-CN, GPP is derived by multiplying leaf-level photosynthesis by leaf area index (LAI). Changes in total projected LAI in the *downregulation* run are consistent with changes in GPP, with significant increases in grassland/steppe and savanna and decreases in tropical rainforest and boreal forest regions (**Figure 9**). Total projected LAI in the moisture-limited regions increases by more than 40% and leads to a global increase of 3.9%. So, global and regional LAI changes explain GPP changes in the *downregulation* run. The simulated results of GPP are consistent with recent findings based on observational analysis and terrestrial ecosystem modeling that the effect of water availability on GPP is large in savannas, shrublands, grasslands, and agricultural areas, but relatively less in tropical and boreal forests (Beer *et al*., 2010; Felzer *et al*., 2011).

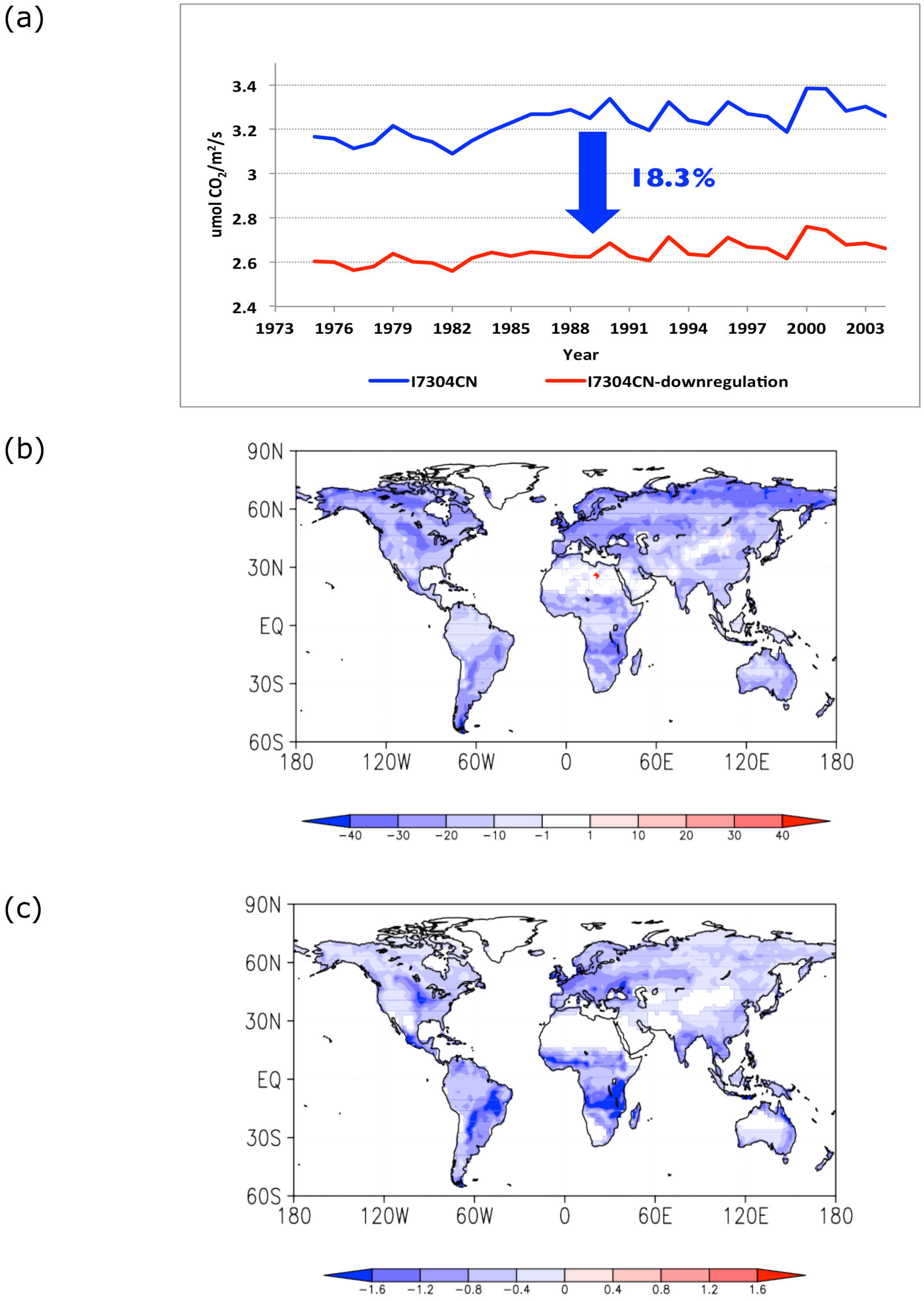

Figure 3. Comparisons of *downregulation* with *control* runs for leaf photosynthesis, where (a) globally averaged annual mean over 60°S-90°N, (b) percentage changes in *downregulation* compared with *control* runs (%), and (c) differences between *downregulation* and *control* runs (umol/CO_2/m^2/s).

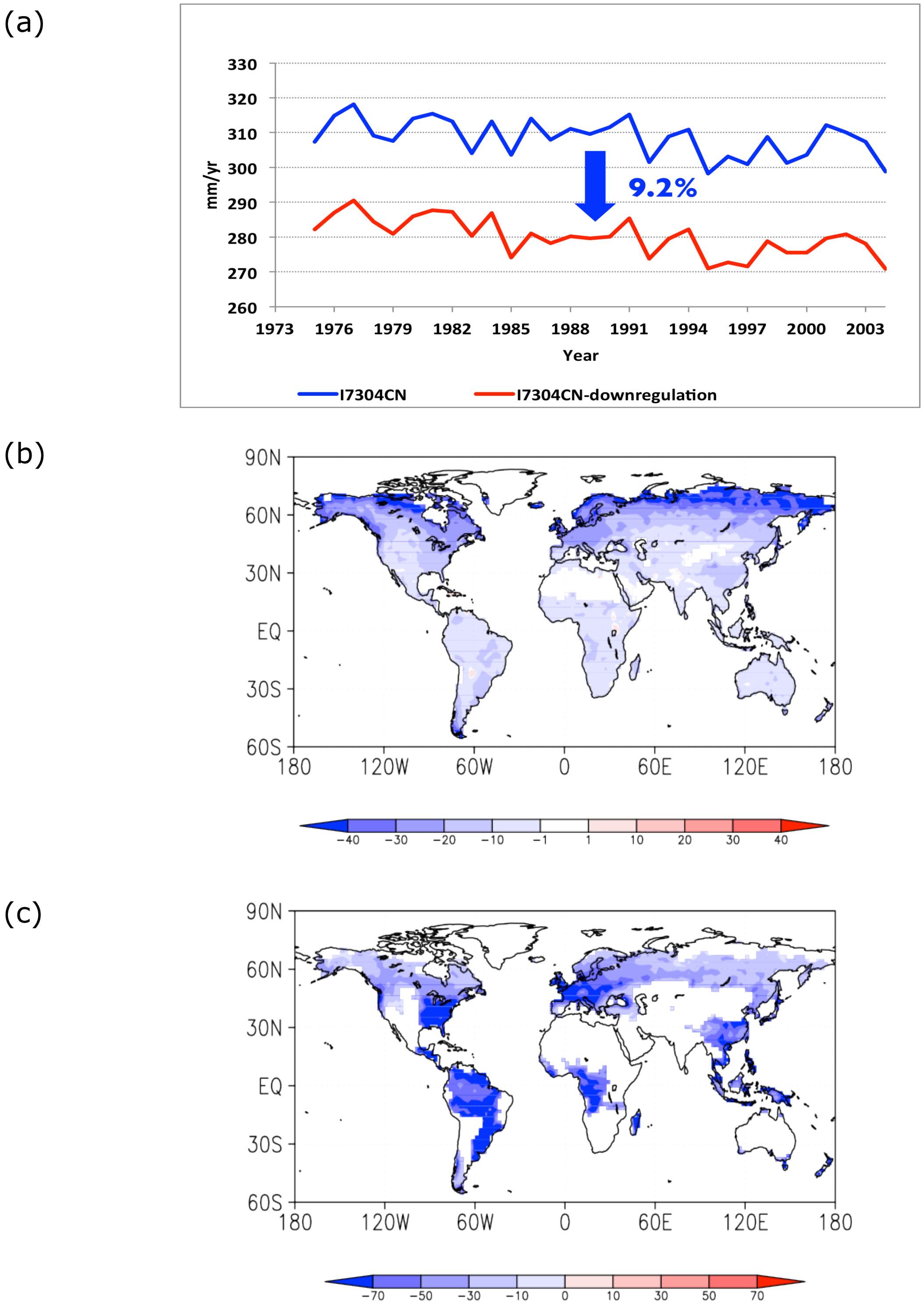

Figure 4. Same as in Figure 3, but for canopy transpiration, where (a) globally averaged annual mean over 60°S-90°N, (b) percentage changes in *downregulation* compared with *control* runs (%), and (c) differences between *downregulation* and *control* runs (mm/year).

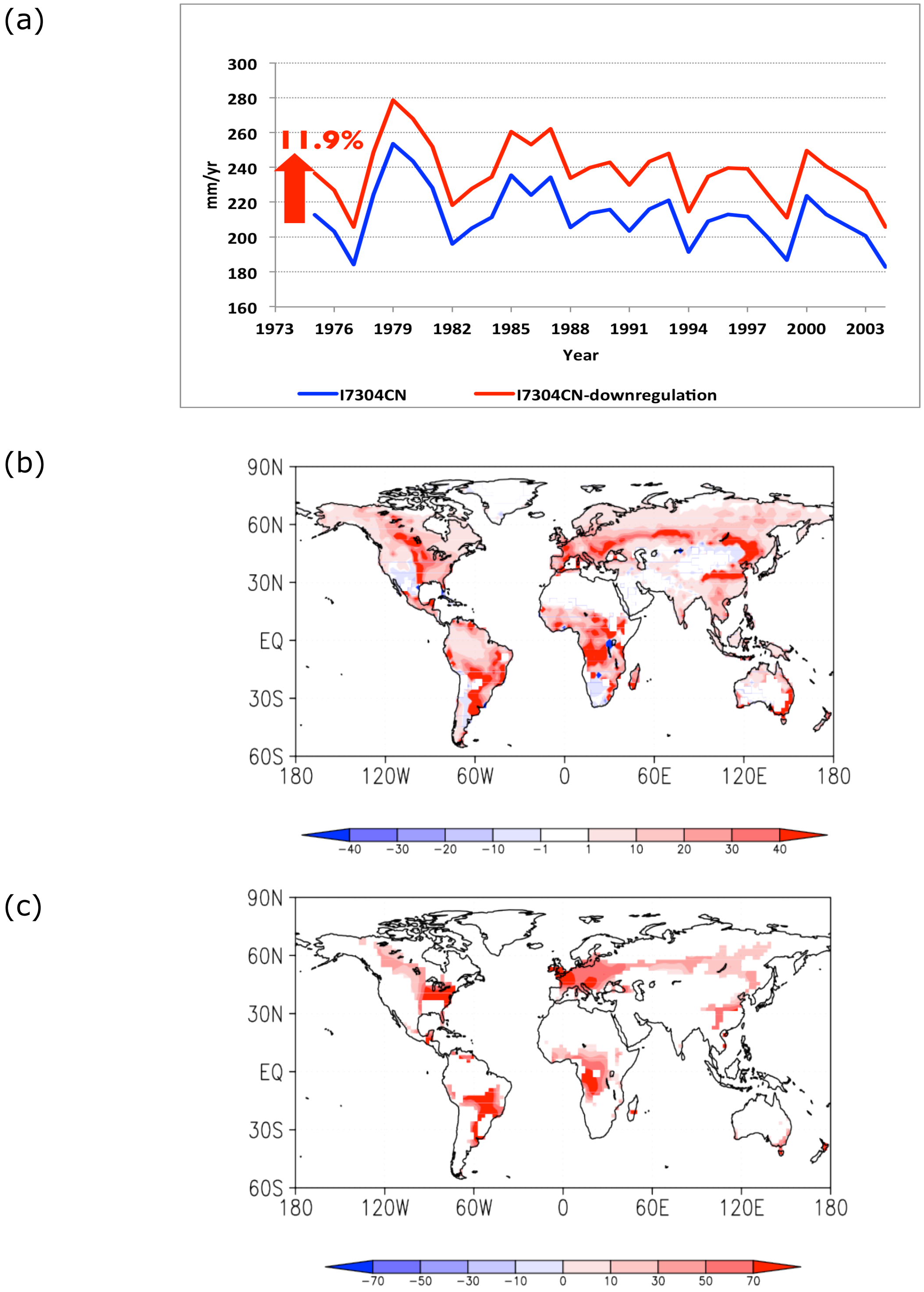

Figure 5. Same as in Figure 3, but for total liquid runoff, where (a) globally averaged annual mean over 60°S-90°N, (b) percentage changes in *downregulation* compared with *control* runs (%), and (c) differences between *downregulation* and *control* runs (mm/year).

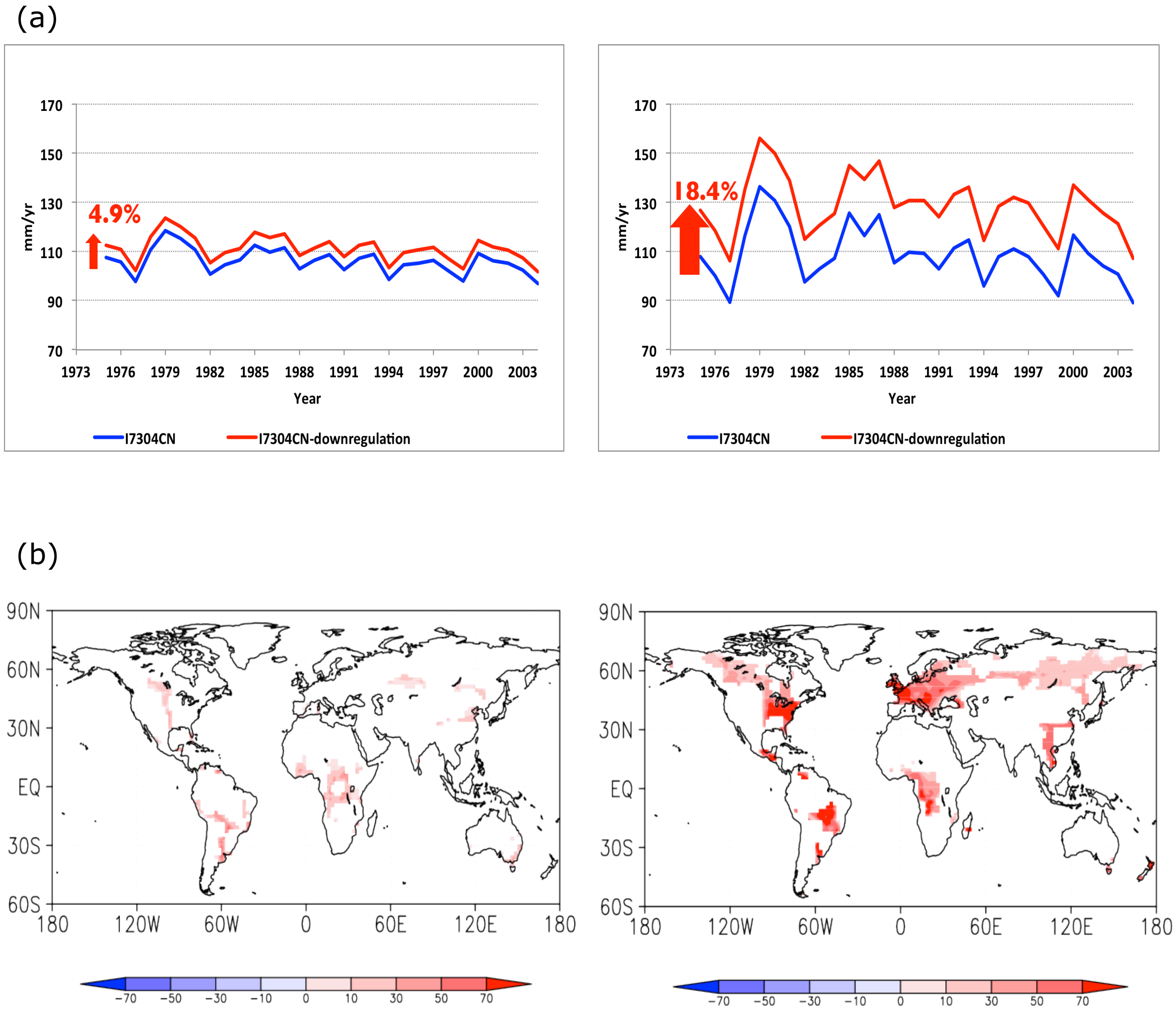

Figure 6. Same as in Figure 3, but for surface runoff (left) and subsurface runoff (right), where (a) globally averaged annual mean over 60°S-90°N and (b) differences between *downregulation* and *control* runs (mm/year).

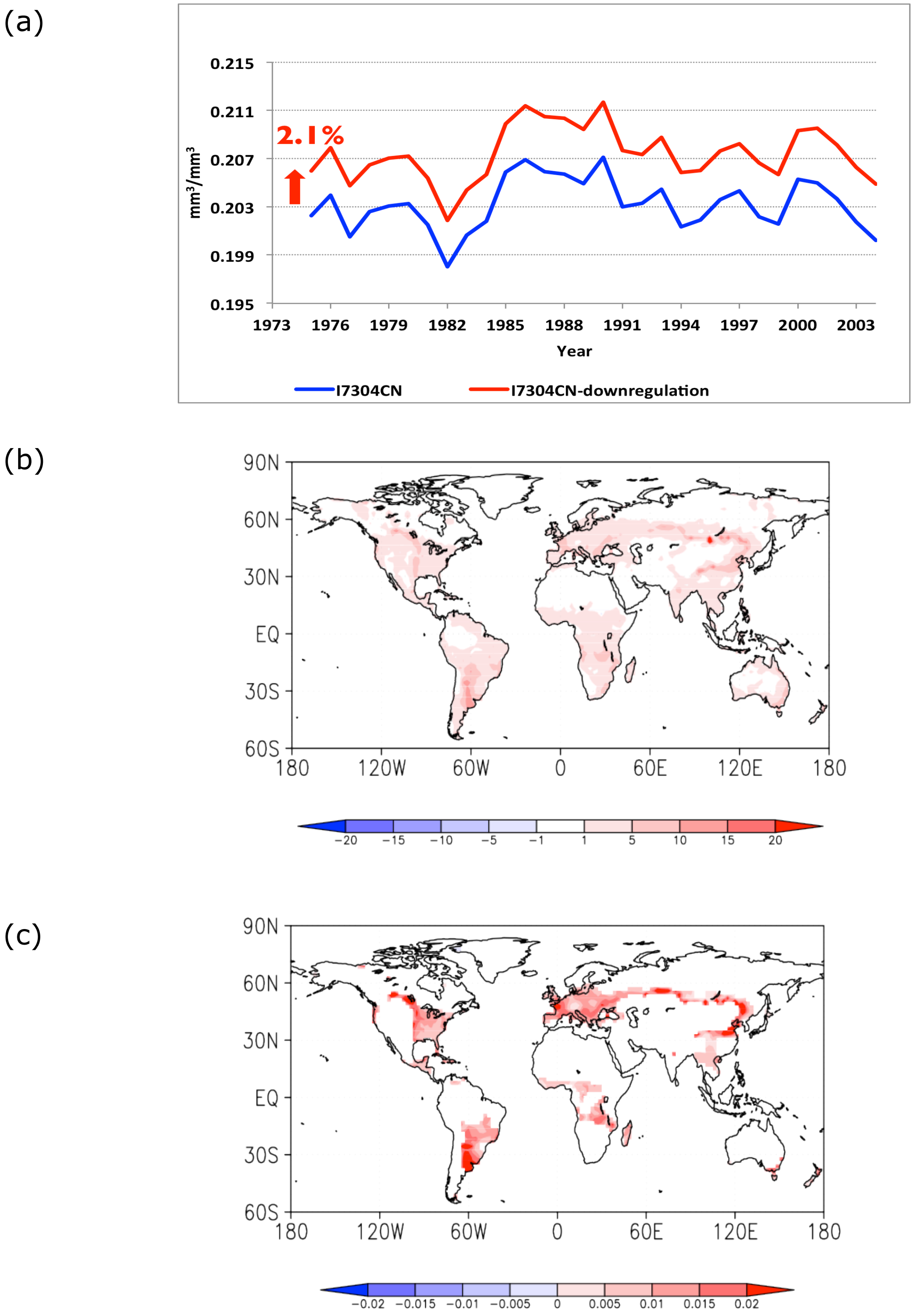

Figure 7. Same as in Figure 3, but for volumetric soil water, where (a) globally averaged annual mean over 60°S-90°N, (b) percentage changes in *downregulation* compared with *control* runs (%), and (c) differences between *downregulation* and *control* runs (mm^3/mm^3).

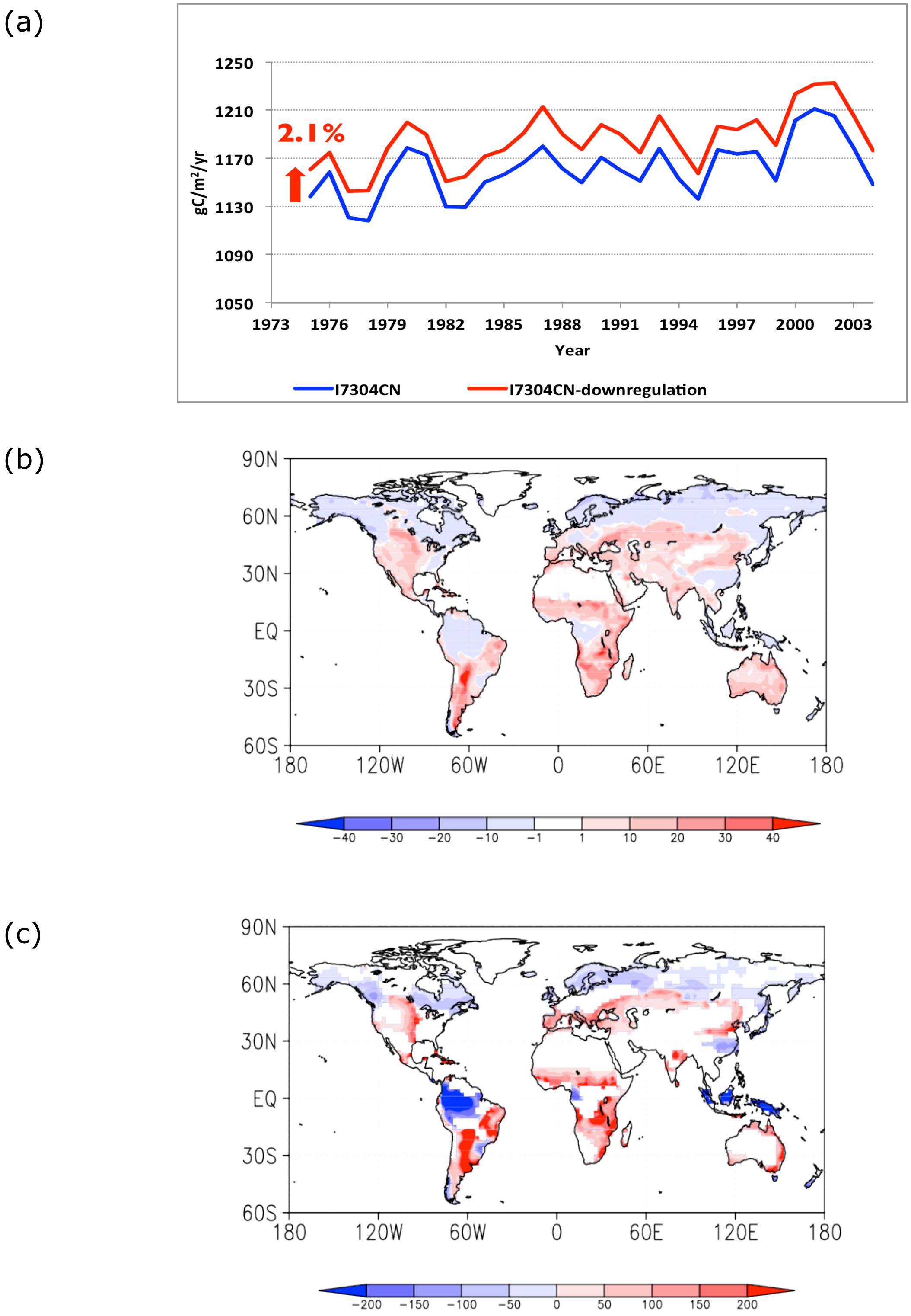

Figure 8. Same as in Figure 3, but for GPP, where (a) globally averaged annual mean over 60°S-90°N, (b) percentage changes in *downregulation* compared with *control* runs (%), and (c) differences between *downregulation* and *control* runs (gC/m^2/yr).

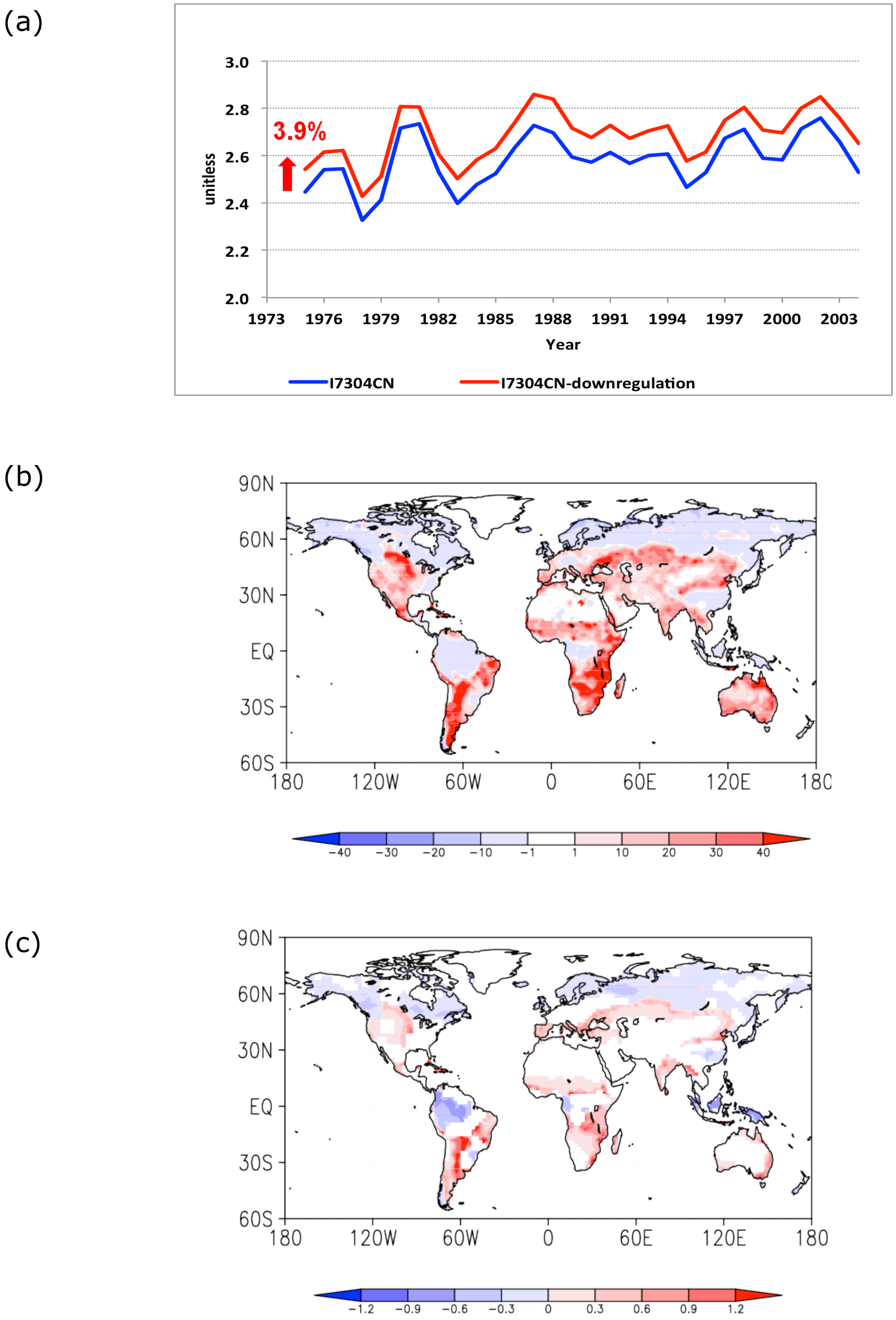

Figure 9. Same as in Figure 3, but for total projected leaf area index, where (a) globally averaged annual mean over 60°S-90°N, (b) percentage changes in *downregulation* compared with *control* runs (%), and (c) differences between *downregulation* and *control* runs (unitless).

3.2 Evaluating Model Outputs

We examine if there is an improvement in simulating carbon and water fluxes in the *downregulation* run, relative to the *control* run. We base the evaluation on latent heat fluxes (LE) and GPP from FLUXNET-MTE for 1982-2004 and surface and subsurface runoff from GSWP-2 for 1986-1995. We first evaluate LE as the sum of canopy transpiration, canopy evaporation, and ground evaporation in CLM4-CN, which is essentially the same as total evapotranspiration (mm/year), but in energy units (W/m^2). The global spatial distribution of annual mean LE for 1982-2004 from CLM4-CN *control* is generally consistent with that from FLUXNET-MTE (**Figures 10**a and b). LE is largest in tropical climates followed by midlatitude humid climates in East Asia, eastern North America, and western and central Europe. However, the magnitude of LE from CLM4-CN is different from FLUXNET-MTE, with high biases in the tropics and mid-latitudes by 30-40 W/m^2 (Figure 10c). In the *downregulation* run, LE decreases from the *control* case, which is due to a significant reduction in canopy transpiration (Figure 10d). Decreasing LE in the *downregulation* run reduces high biases in the tropics and mid-latitudes. Decreasing LE in the northern high-latitudes may increase low biases of LE over the regions, but the biases are relatively less than tropical biases. Annual mean LE is zonally averaged over 15°S-15°N (Figure 10e). LE from the CLM4-CN *control* shows high biases, so decreasing LE in the *downregulation* run reduces the biases by 5-10 W/m^2 in the tropics.

As shown in Figure 5, decreasing canopy transpiration results in a significant increase in total runoff in the *downregulation* run, mainly due to changes in subsurface runoff. We evaluate total runoff (sum of surface and subsurface runoff) from CLM4-CN using the GSWP-2 data from 1986-1995. The global spatial distributions of annual mean runoff from the CLM4-CN *control* show large runoff in western Amazon, Southeast Asia, Ganges River in South Asia, coastal regions of the Gulf of Alaska, and western Scandinavia, which are consistent with those from GSWP-2 (**Figures 11**a and b). Zonally averaged annual mean of runoff from CLM4-CN is generally well captured, with two peaks in the equatorial and northern high-latitude regions, even though there are low biases in the highest runoff regions (Figure 11e-Globe). The spatial differences between the CLM4-CN *control* and GSWP-2 show that CLM4-CN runoff is lower than GSWP-2 across the globe, with significant low biases in the tropics and northern high-latitudes by 300 mm/year (Figure 11c). In the *downregulation* run, runoff increases across the globe from the *control* case (Figure 11d). So, the increasing runoff reduces low runoff biases in the current CLM4-CN, especially in the tropics, by 50-100 mm/year (Figure 11e-Tropcis) and the northern high-latitudes by 20 mm/year (Figure 11e-Northern high-latitudes).

Lastly, we evaluate GPP from the CLM4-CN *control* and *downregulation* runs using GPP from FLUXNET-MTE for 1982-2004. The global spatial distributions of GPP from the CLM4-CN *control* generally capture those from the observations, but CLM4-CN simulates GPP too high in the tropical regions (**Figures 12**a and b). In other regions, there are high model biases in boreal forests, but low biases in savanna in Africa and South America (Figure 12c). On the other hand, GPP from the *downregulation* run is less in the tropical and boreal forest regions, but more in grassland/steppe and savanna regions, relative to GPP from the *control* run (Figure 12d). So, the spatially different changes in GPP can reduce GPP biases in the current CLM4-CN. For example, annual mean GPP in the tropical Amazon in the *downregulation* run reduces high model biases over the tropical regions as a whole (Figure 12e).

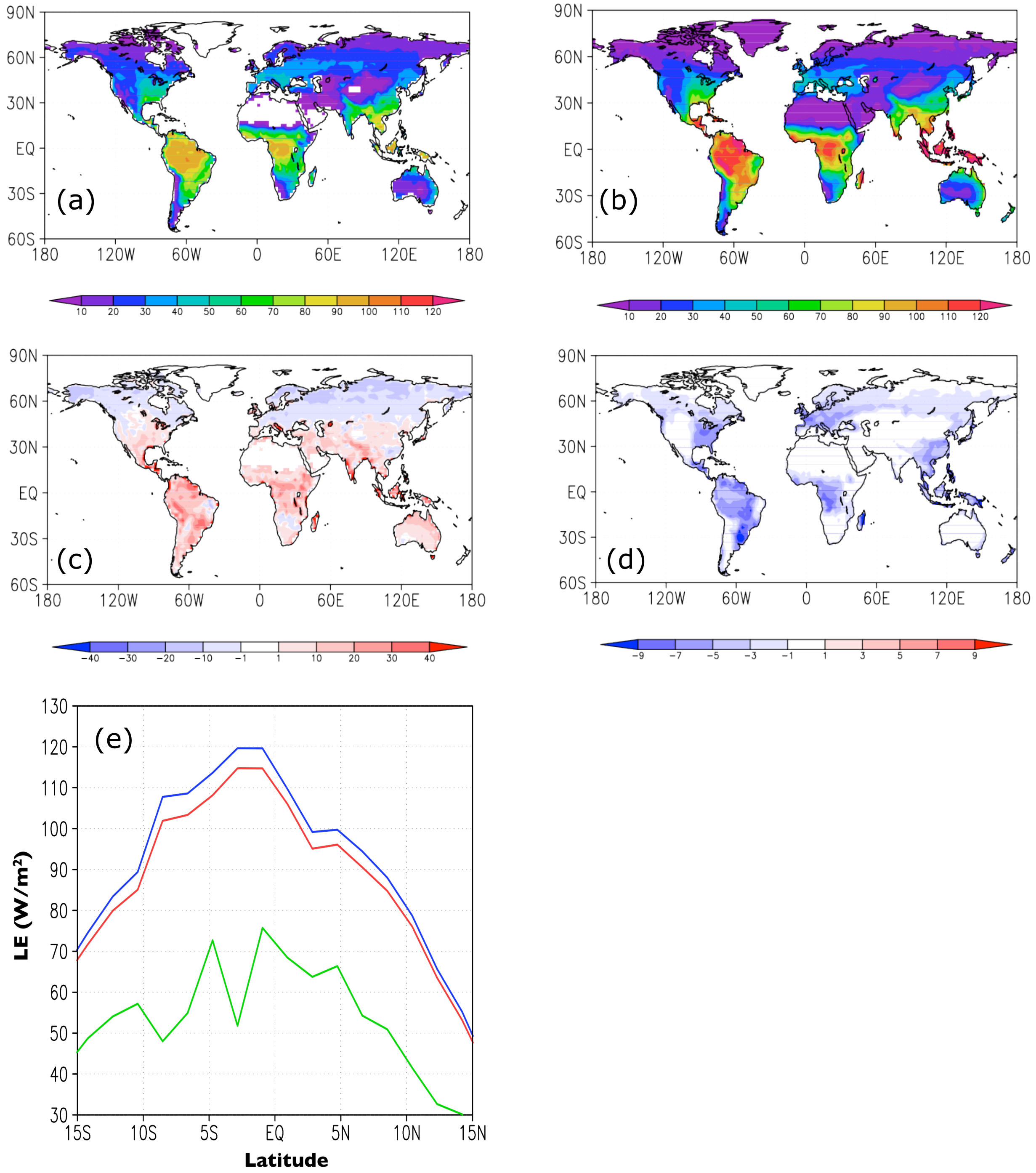

Figure 10. Evaluations of CLM4-CN *control* and *downregulation* with FLUXNET MTE for LE (W/m^2), where (a) FLUXNET MTE, (b) *Control*, (c) *Control* – FLUXNET MTE, (d) *Downregulation* – *Control*, and (e) zonally averaged annual mean in the tropics. (e) FLUXNET MTE (green), *control* (blue), and *downregulation* (red).

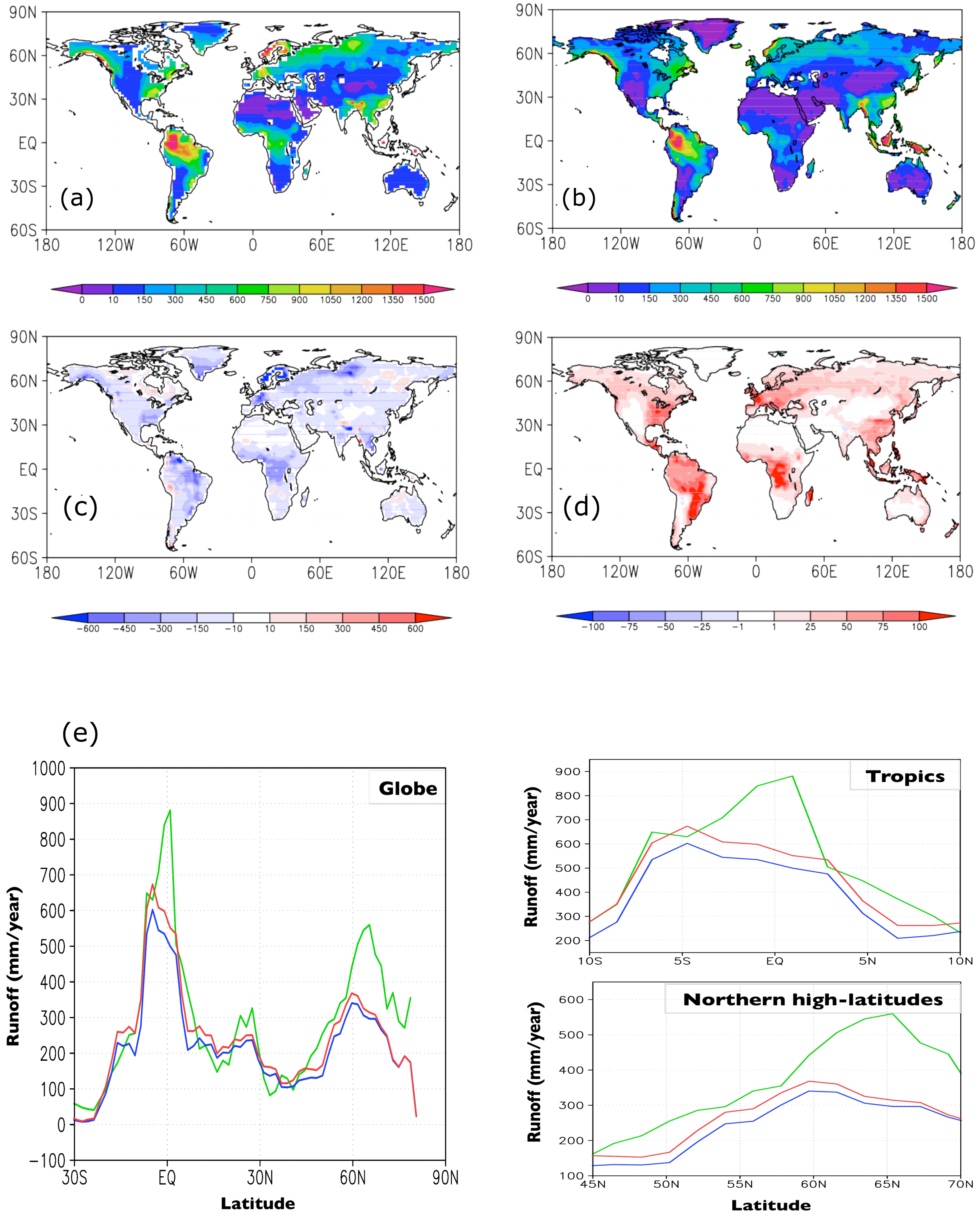

Figure 11. Evaluations of CLM4-CN *control* and *downregulation* with GSWP2 for total runoff, where (a) GSWP2, (b) *Control*, (c) *Control* – GSWP2, and (d) *Downregulation* – *Control*, and (e) zonally averaged annual mean in the globe, tropics, and northern high-latitudes. (e) GSWP2 (green), control (blue), and downregulation (red).

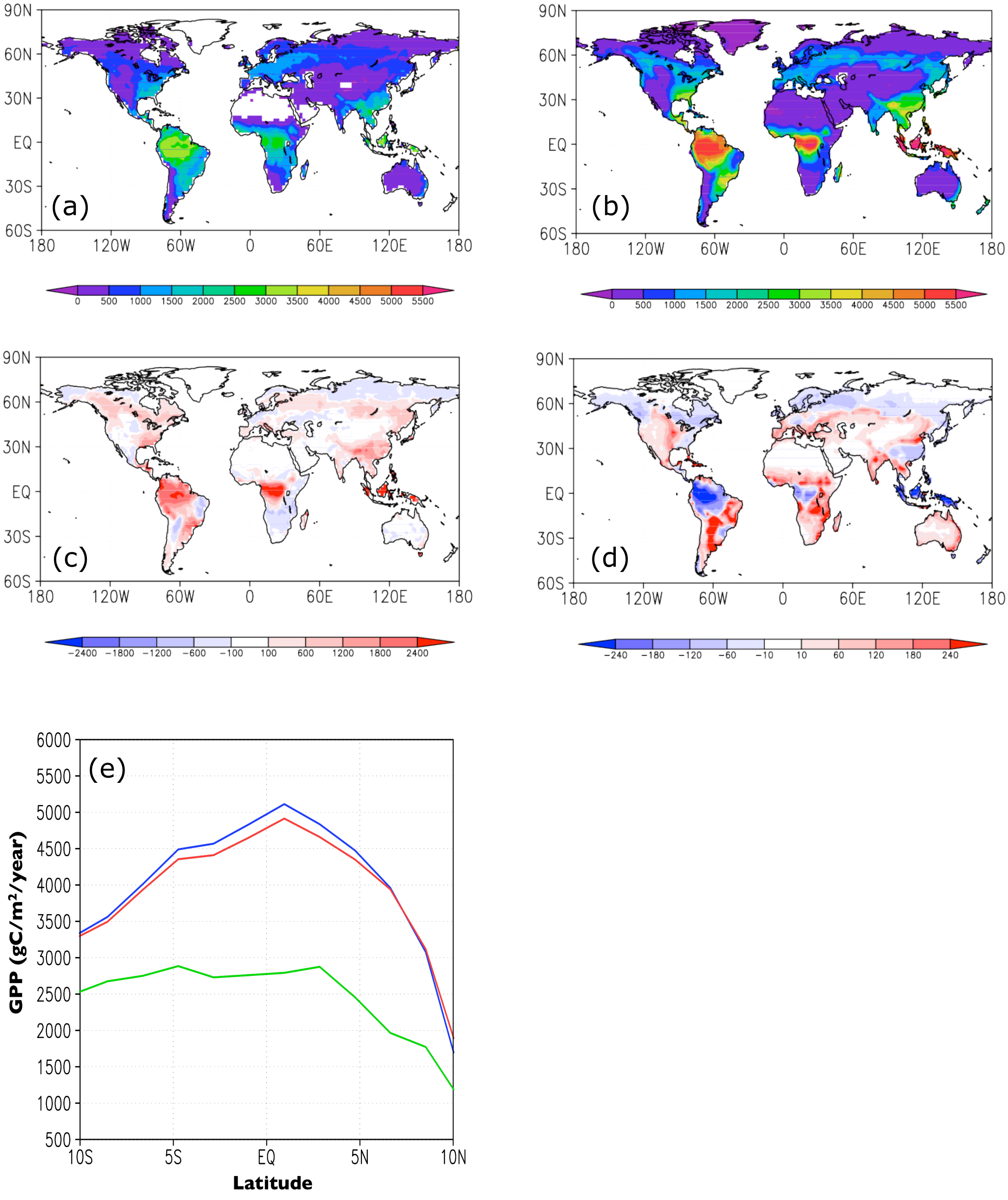

Figure 12. Evaluations of CLM4-CN *control* and *downregulation* with FLUXNET MTE for GPP (gC/m^2/yr), where (a) FLUXNET MTE, (b) *Control*, (c) *Control* – FLUXNET MTE, (d) *Downregulation* – *Control*, and (e) Zonally averaged annual mean in the tropical Amazon. (e) FLUXNET MTE (green), control (blue), and downregulation (red).

4. CONCLUSIONS AND REMARKS

Nitrogen limitation on the leaf-level significantly affects hydrological processes in CLM4-CN. In the *downregulation* simulations applying nitrogen limitation to stomata, nitrogen limitation reduces leaf photosynthesis, which leads to a reduction in canopy transpiration by decreasing stomatal conductance, and results in increasing total runoff. Globally averaged leaf photosynthesis is down-regulated by 18.3%, with significant decreases over most vegetated regions of the globe. So, the photosynthesis used to determine stomatal conductance is lower, and thereby global annual canopy transpiration decreases by 9.2%. Significant increases in total runoff by reducing transpiration occur in tropical savanna and mid-latitude grassland/steppes, where runoff increases by more than 40%. It is mainly due to increasing subsurface runoff and only partially by increasing surface runoff. In addition, more available soil water results from decreasing canopy transpiration, which reduces water stress and provides more favorable condition for plant productivity in moisture-limited regions. Thus, changes in the hydrological cycle by nitrogen limitation affect changes in GPP through two different processes. In the tropical and boreal forest regions, reduced leaf photosynthesis by nitrogen limitation directly decreases GPP. On the other hand, in the grassland/steppe and savanna regions, the down-regulated photosynthesis indirectly affects GPP by the photosynthesis-stomatal conductance feedback: less leaf photosynthesis-less transpiration-more soil water (less water stress)-higher GPP. So, GPP in the *downregulation* run decreases in the relatively moist regions, but increases in the relatively moisture-limited regions, relative to the *control*.

Significant changes in canopy transpiration and runoff due to nitrogen limitation on the leaf-level reduce the biases of LE and runoff from CLM4-CN, compared with those from observational and multi-model ensemble data. High biases of LE in the tropics and mid-latitudes are reduced by decreasing LE in the *downregulation* run. Low biases of total runoff in the tropics and northern-high latitudes are also reduced by increasing runoff, mainly due to increasing subsurface runoff. In addition, CLM4-CN with leaf-level nitrogen limitation reduces high GPP biases in tropical and boreal forests and low GPP biases in savanna regions, even though there are still high rates of GPP in the tropics. To reduce the remaining high GPP biases, we will apply the photosynthesis-stomatal conductance parameterization taken by Bonan *et al.* (2011) in CLM4 to CLM4-CN with leaf-level nitrogen limitation.

As shown in Figure 1, there are two different feedbacks in carbon and water coupling in stomata. Atmospheric CO_2 is positively coupled with stomatal conductance by internal leaf CO_2 level, but it is negatively coupled with stomatal conductance by leaf surface CO_2 concentration. Changes in future atmospheric CO_2 concentration will have differing effects on hydrological processes by these positive and negative couplings. Another interesting issue is whether changes in hydrological processes due to leaf-level nitrogen limitation could be large enough to alter near-surface and possibly large-scale climate conditions through changes in surface heat and moisture budgets. Furthermore, it may be important to explore how changes in runoff from nitrogen limitation in the northern high-latitudes affect the freshwater flow into the Arctic and the resulting ocean conveyor belt circulation (i.e. Thermohaline circulation). To address these issues, coupled model simulations including atmosphere, ocean, and ice with CLM4-CN are needed.

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5. REFERENCES

Ball, J. T., I. E. Woodrow, and J. A. Berry, 1987: A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, in Progress in Photosynthesis Research, vol. 4, edited by J. Biggins, pp. 221–224, Martinus Nijhoff, Dordrecht, Netherlands.

Beer, C., M. Reichstein, E. Tomelleri, P. Ciais, M. Jung, N. Carvalhais, C. Rödenbeck, M. A. Arain, D. Baldocchi, G. B. Bonan, A. Bondeau, A. Cescatti, G. Lasslop, A. Lindroth, M. Lomas, S. Luyssaert, H. Margolis, K. W. Oleson, O. Roupsard, E. Veenendaal, N. Viovy, C. Williams, F. I. Woodward, and D. Papale, 2010: Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science*, **329,** 834–838, doi:10.1126/science.1184984.

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

Bonan, G. B., P. J. Lawrence, K. W. Oleson, S. Levis, M. Jung, M. Reichstein, D. M. Lawrence, and S. C. Swenson, 2011: Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data. *J. Geophys. Res.*, **116,** G02014, doi:10.1029/2010JG001593.

Boone, A, I. Poccard-Leclerq, Y. Xue, J. Feng, and P. de Rosnay, 2010: Evaluation of the WAMME model surface fluxes using results from the AMMA land-surface model intercomparison project. *Clim. Dyn.,* doi:10.1007/s00382-009-0653-1.

Chen, H., R. E. Dickinson, Y. Dai, and L. Zhou, 2011: Sensitivity of simulated terrestrial carbon assimilation and canopy transpiration to different stomatal conductance and carbon assimilation schemes. *Clim. Dyn.*, doi:10.1007/00382-00010-00741-00382.

Collatz, G. J., J. T. Ball, C. Grivet, and J. A. Berry, 1991: Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: A model that includes a laminar boundary layer. *Agric. Forest Meteorol.,* **54,** 107–136, doi:10.1016/0168-1923(91)90002-8.

Dirmeyer, P. A., X. Gao, M. Zhao, Z. Guo, T. Oki, and N. Hanasaki, 2006: GSWP-2: multimodel analysis and implications for our perception of the land surface. *Bull. Am. Meteorol. Soc.,* **87,** 1381-1397.

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.

Felzer, B. S., T. W. Cronin, J. M. Melillo, D. W. Kicklighter, C. A. Schlosser, and S. R. S. Dangal, 2011: Nitrogen effect on carbon-water coupling in forests, grasslands, and shrublands in the arid western United States. *J. Geophys. Res.,* **116,** G03023, doi:10.1029/2010JG001621.

Jung, M., M. Reichstein, and A. Bondeau, 2009: Towards global empirical upscaling of FLUXNET eddy covariance observations: Validation of a model tree ensemble approach using a biosphere model. *Biogeosciences,* **6,** 2001–2013, doi:10.5194/bg-6-2001-2009.

Jung, M., M. Reichstein, H. Margolis, A. Cescatti, A. Richardson, A. Arain, A. Arneth, C. Bernhofer, D. Bonal, J. Chen, D. Gianelle, N. Gobron, G. Kiely, W. Kutsch, G. Lasslop, B. Law, A. Lindroth, L. Merbold, L. Montagnani, E. Moors, D. Papale, M. Sottocornola, F. P. Vaccari, and C. Williams, 2011: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J. Geophys. Res.,* **116,** G00J07, doi:10.1029/2010JG001566.

Langley, J. A., and J. P. Megonigal, 2010: Ecosystem response to elevated CO_2 levels limited by nitrogen-induced plant species shift. *Nature,* 466, 96–99.

Lawrence, D. M., K. W. Oleson, M. G. Flanner, P. E. Thorton, S. C. Swenson, P. J. Lawrence, X. Zeng, Z.-L. Yang, S. Levis, K. Skaguchi, G. B. Bonan, and A. G. Slater, 2011: Parameterization improvements and functional and structural advances in version 4 of the Community Land Model. *J. Adv. Model. Earth Syst.*, **3,** M03001, doi:10.1029/2011MS000045.

McGuire, A. D., J. M. Melillo, L. A. Joyce, D. W. Kicklighter, A. L. Grace, B. Moore, and C. J. Vorosmarty, 1992: Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. *Global Biogeochem. Cycles*, **6,** 101–124.

Oleson, K. W., D. M. Lawrence, G. B. Bonan, M. G. Flanner, E. Kluzek, P. J. Lawrence, S. Levis, S. C. Swenson, P. E. Thornton, A. Dai, M. Decker, R. Dickinson, J. Feddema, C. L. Heald, F. Hoffman, J.-F. Lamarque, N. Mahowald, G.-Y. Niu, T. Qian, J. Randerson, S. Running, K. Sakaguchi, A. Slater, R. Stockli, A. Wang, Z.-L. Yang, X. Zeng, X. Zeng, 2010: Technical description of version 4.0 of the Community Land Model (CLM). NCAR Tech. Note NCAR/TN-478+STR, 257 pp., NCAR, Boulder, Colorado.

Sokolov, A. P., D. W. Kicklighter, J. M. Melillo, B. S. Felzer, C. A. Schlosser, and T. W. Cronin, 2008: Consequences of considering carbon/nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. *J. Clim.,* **21,** 3776–3796.

Thornton, P. E., and N. A. Rosenbloom, 2005: Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model. *Ecol. Modell.*, **189,** 25–48.

Thornton, P. E., J.-F. Lamarque, N. A. Rosenbloom, and N. M. Mahowald, 2007: Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. *Global Biogeochem. Cycles*, **21,** GB4018, doi:10.1029/2006GB002868.

Thornton, P. E., 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,** 2099-2120, doi:10.5194/bg-6-2099-2009.

Vitousek, P. M., and R. W. Howarth, 1991: Nitrogen limitation on land and in the sea: How can it occur?. *Biogeochemistry,* **13,** 87–115.

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