Effects of Vegetation Activities and Climate Change on Evapotranspiration, Runoff, and Soil Moisture over the Conterminous U.S. during 1983-2009

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Introduction:

Evidence indicates that the global terrestrial water cycle has been altered by environmental change and human activities during the last century [Hutjes et al., 1998; Jackson et al., 2005; Gedney et al., 2006]. Remotely sensed data detected an earlier greenness of vegetation and a longer growing season in the Northern Hemisphere during the last several decades and these warming are thought to be closely linked with enhanced ecosystem productivities and carbon sequestrations in northern hemisphere [Myneni et al., 1997; Zhou et al., 2001; Nemani et al., 2003]. How this feedback of terrestrial ecosystems to climate change influence the regional water cycles under various spatial scales by working together with meteorological and atmospheric (i.e. effects of increasing atmospheric CO2 concentration on stomatal conductance and water use efficiency) factors are not clear [Field et al., 1995; Gedney et al., 2006; Dai et al., 2009; Jung et al., 2010; Wang and Dickinson, 2012; Liu et al., 2013a]. This study is to investigate how vegetation activities, in combination of climate change and CO2 fertilization effect, could affect the long-term and seasonal variations of terrestrial water fluxes and SM over the conterminous United States during 1983-2009.

Methods and Data:

The three-layer Variable Infiltration Capacity (VIC) model with improved algorithms on snow accumulation and ablation was used in this study [Liang et al., 1994, 1996; Cherkauer and Lettenmaier, 1999, 2003; Cherkauer et al., 2003]. To estimate effects of phenology on hydrological processes, we used the 15-day Global Leaf Area Index product (LAI3g) with a 1/12 degree latitude-longitude resolution, which was generated from third generation of Global Inventory Modeling and Mapping Studies (GIMMS) NDVI (NDVI3g) by using a Feed-Forward Neural Network method [Zhu et al., 2013]. For considering uncertainties from the meteorological data and resolution, we used two sets of climate data to drive the model: one is a newly developed meteorological data gridded at 1/16 degree resolution which were based on approximately 20,000 NOAA Cooperative Observer stations [Livneh et al., 2013] (hereafter Livneh-Met); another data sets is the forcing data for Phase 2 of the North American Land Assimilation System (NLDAS-2) (http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php) at a resolution of 1/8th degree resolution (hereafter NLDAS-Met). To separate contributions of climate change factors (T & P) and vegetation activities (LAI), a series of factor-controlled simulation experiments were conducted (Table 1). They include "Base Run" that all factors are transient, and single factor simulations that only T, P, LAI, or atmospheric CO2 concentration are fixed while other factors are transient (Table 1). The differences in simulation results between the "Base Run" and single factor control experiment represent the net effects of that single factor on hydrological processes in the context of interactions with other factors.

Table 1 Simulation experiments

Name of Experiments	Control Factors			
	T	P	LAI	CO_2
Base Run	Tr	Tr	Tr	Tr
FixT	M	Tr	Tr	Tr
FixP	Tr	M	Tr	Tr
FixCO_2	Tr	Tr	Tr	M
FixLAI	Tr	Tr	M	Tr
FClimate	Tr	Tr	M	M

Abbreviations: T: temperature; P: precipitation; LAI: leaf area index; CO_2: atmospheric CO_2 concentration; Tr: Transient data, i.e. annual data; M: Mean-climate during 1983-2009 or constant atmospheric CO_2 in 1983.

Results:

Long-term trends in driving forces and water fluxes

The continental US experienced significant increases in annual mean LAI (+0.026/decade, or +5.6% in total during 1983-2009) and annul mean T (+0.21 0.05ºC/decade) during 1983-2009 (Fig. 1-a & 1-b). The annual (water year, i.e. Oct. – Sep.) total P has no significant trend during the study period while it had a significant decrease in cool season (Oct. – Mar.). According to simulated results, the changing climate, LAI, and atmospheric CO2 caused significant spatial variations in long-term trends, inter-annual fluctuations, and seasonal patterns.

Contributing factors to the interannual variations and long-term trends

Simulation results indicated that P is the dominant factor controlling the interannual fluctuations of water fluxes and SM. The Pearson Correlation Coefficients (r) between P-caused and all factors-caused variations are 0.965, 0.987, and 0.989 on ET, R, and SM, respectively, over the Conterminous US (Fig. 2; Table 2). However, all other factors (including LAI, T, and atmospheric CO2) made higher contributions to the overall long-term trends in hydrological processes than to the interannual variations (Table 2). Overall, CO2 has minor effects on the interannual fluctuations and long-term trends in water cycles, but it still compensated about 50% of total effects of LAI on ET, R, and SM during the study period over the conterminous US (Table 2).

Each factor's relative contributions on water cycles varied in each season. T and LAI influenced larger areas in ET's long-term trend during the cool seasons than warm seasons. During cool season, 53% of land was dominantly controlled by P, followed by T (28%) and LAI (18%) in the long-term trends of ET. LAI also played the second dominant roles on the interannual variations of ET during the cool season which covered 26% of total land area (Fig.4).

Comparisons with remotely sensed data

VIC succeeds in catching the monthly variations of surface (Pearson correlation coefficient, r, between VIC and AMSR-E is 0.73) and total water content (r = 0.94 in monthly anomalies between VIC-simulated total water content and GRACE-derived terrestrial water storage) over the conterminous US (Figs. 5a & 5b). On the ET simulations, VIC is successful in retrieving the monthly fluctuations (r = 0.98 with MTE up-scaled ET) while it has difficulties in catching the magnitude of inter-annual fluctuations such as underestimations in dry years 1988, 2000, and 2002 (Fig. 5c).

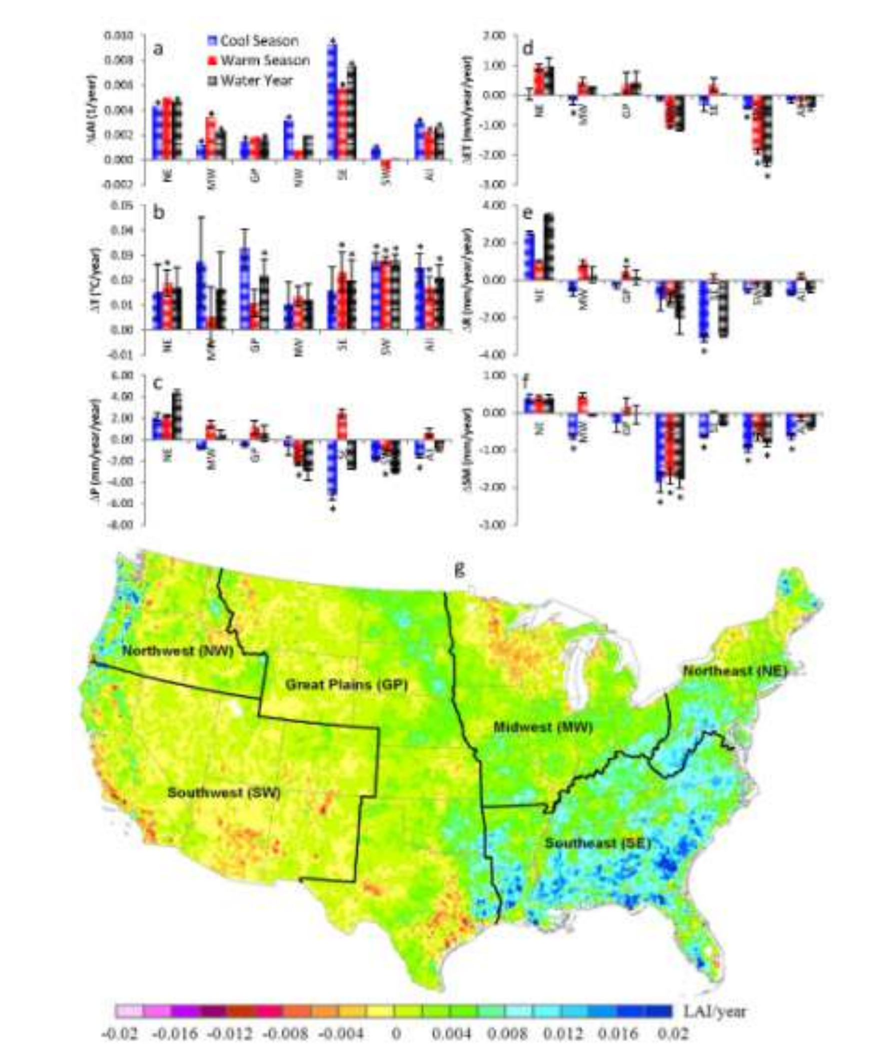

Figure 1 Trends in annual mean temperature (*T*), annual precipitation (*P*), leaf area index (*LAI*), and simulated evapotranspiration (*ET*), runoff (*R*), and soil moisture (*SM*) over each region of the conterminous US during 1983-2009. Blue bar represents cool season (October - March); red bar represents warm season (April - September), and black bar is average over water year. Asteroid over each bar represents the significance of the trends (t-test *p-value* < 0.05 on either NLDAS-Met or Livneh-Met). The error bar is the range of NLDAS-Met and Livneh-Met or simulation results driven by these datasets.

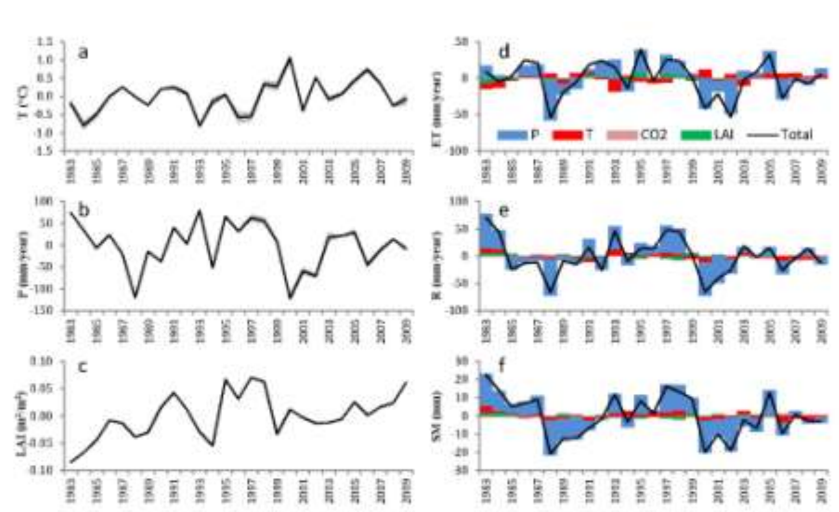

Figure 2 Anomaly of interannual variations of annual mean temperature (T), annual precipitation (P), leaf area index (LAI), and simulated evapotranspiration (ET), runoff (R), and soil moisture (SM) during 1983-2009. The baseline period is 1983-2009. The shaded area in a & b is the range of Livneh-Met and NLDAS-Met. Different colored bar represent effects of each factor on the interannual variations: blue: P, red: T, pink: atmospheric CO2 concentration, green: LAI, and black line is the total effects (i.e. "Base" run).

Table 2 Contributions of climate factor, LAI, and atmospheric CO2 to the long-term and interannual variations of hydrologic variables during 1983-2009 over the Conterminous US

Variables	Factor	T	P	CO_2	LAI	All factors
ET	Trend (mm/year/year)	0.23	-0.26	-0.09	0.15	-0.40
	t-test for linear trend (*p*-value)	0.12	0.65	<<0.05*	0.09	0.53
	Pearson's correlation coefficient#	-0.36	0.97	-0.10	0.46	-
Runoff	Trend (mm/year/year)	-0.24	-0.60	0.09	-0.15	-0.54
	t-test for linear trend (*p*-value)	0.06	0.47	<<0.05*	0.07	0.52
	Pearson's correlation coefficient#	0.72	0.99	0.02	-0.01	-
Soil moisture	Trend (mm/year/year)	-0.09	-0.31	0.06	-0.03	-0.38
	t-test for linear trend (*p*-value)	0.04*	0.26	<<0.05*	0.22	0.19
	Pearson's correlation coefficient#	0.69	0.99	-0.21	-0.03	-

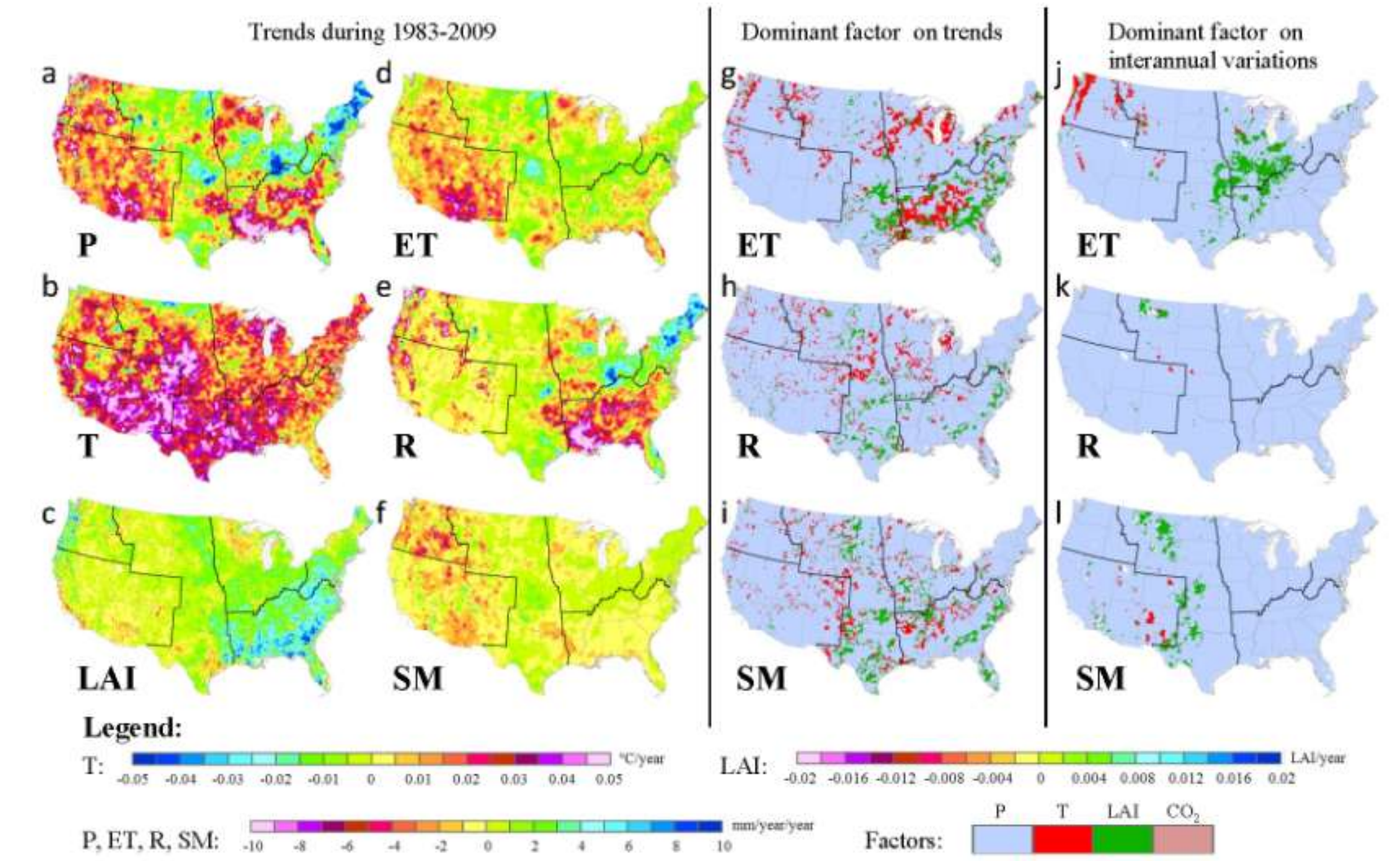

Figure 3 Trends in driving forces (including annual mean temperature - T, annual precipitation – P, leaf area index – LAI) and simulated evapotranspiration (ET), runoff (R), and soil moisture (SM) (a-f); and dominant factors on hydrologic long-term trend (g-i) and interannual variations (j-l). The dominant factor on long-term trends is the factor that generated largest absolute linear trends; the dominant factor on interannual variations is the factor that produced highest Pierce Correlation coefficient with all factors-caused variation (i.e. "Base" run). Blue, red, green, and pink colors represent the long-term trends or internnual variations is dominantly controlled by precipitation (P), temperature (T), leaf area index (LAI), and atmospheric CO_2 concentration, respectively.

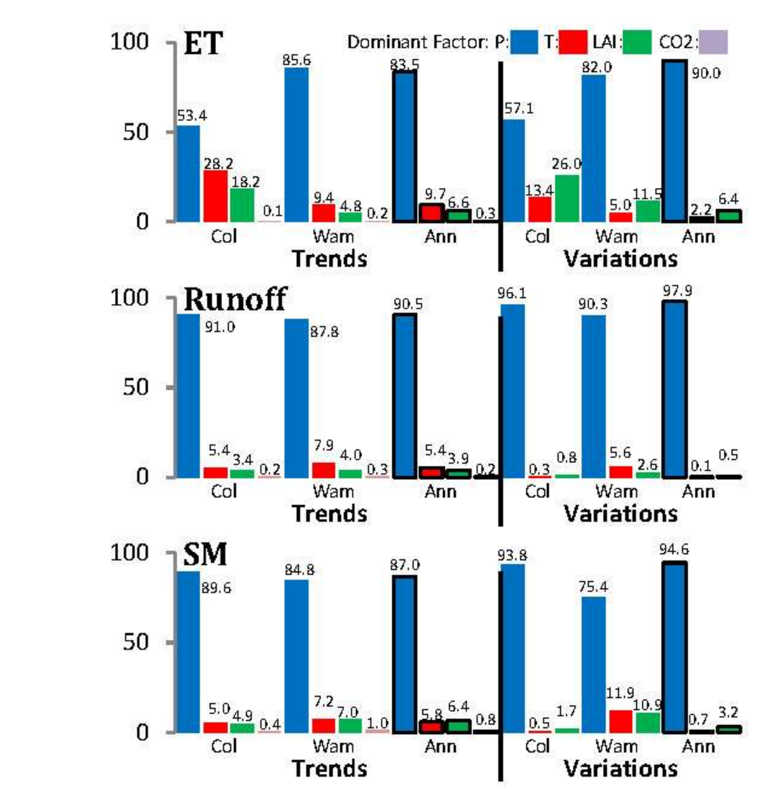

Figure 4. Attributions of LAI (leaf area index), T (annual mean temperature), P (annual precipitation), and CO2 (atmospheric CO2 concentration) on long-term trends and seasonal variations of ET (evapotranspiration), SM (soil moisture), and runoff (R) over the conterminous US during 1983-2009. The value over each bar represents the percentage of grid cells that were dominantly controlled by that factor. .

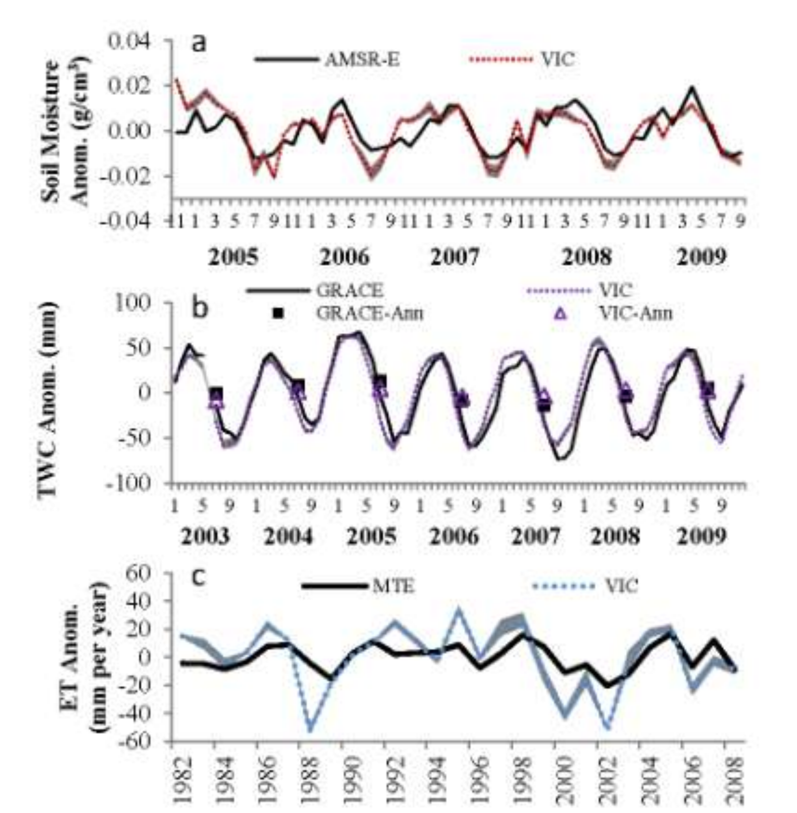

Figure 5. Comparisons of VIC-modeled results with remote sensing-based estimations over the conterminous US during 1983-2009. a) modeled anomalies in surface soil moisture (top 10 cm) against AMSR-E derived surface moisture (~ 1cm); b) model anomalies in total water content (total soil water content plus snowpack equivalent water) against GRACE-derived terrestrial water equivalent; and c) VIC simulated anomalies in annual ET against up-scaled ET from eddy-flux stations.

Conclusions & Discussions:

Simulated results from factor-control experiments indicate that P was the dominant factor controlling the long-term trends and interannual fluctuations of ET, R, and SM over the conterminous US. However, LAI and T took very important roles in regions such as the Southeast, the Northeast, and the Middle West, and particularly during cold seasons. Normally, the increases in LAI enhanced ET and reduced R and SM while the rising atmospheric CO2 concentration compensated half of LAI's effects on long-term trends over the conterminous US during this period. We should emphasize that each factor's contributions to variations of long-term trends in hydrology vary in spatial and temporal domain. Comparisons of model results with remote sensing based estimations (including AMSR-E, GRACE, and up-scaled ET) indicate VIC model succeed in tracking seasonal and interannual anomalies in total water content and ET but has large biases in surface soil moisture. To enhance hydrologic model's capability, coupling with biogeochemical and ecological processes and land use practices in the modeling framework is critical.

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