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The importance of carbon-nitrogen biogeochemistry on water vapor and carbon fluxes as elucidated by a multiple canopy layer higher order closure land surface model

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ABSTRACT

The carbon-nitrogen (CN) biogeochemistry and the prognostic canopy structure scheme used in the Community Land Model version 4.5 (CLM4.5) are integrated into the multiple canopy layer higher order closure Advanced Canopy-Atmosphere-Soil Algorithm (ACASA). The ACASA-CN model inherits the advantages from ACASA and CLM4.5, and it is the first model that represents fully prognostic terrestrial feedbacks with a higher order closure turbulence scheme and vertically resolved canopy structure. The simulations are evaluated in terms of ecological, biogeophysical and biogeochemical aspects at six AmeriFlux eddy covariance sites encompassing a variety of vegetation types and microclimatic conditions across the continental United States. Our model evaluation shows that ACASA-CN reasonably simulates surface layer properties, such as vegetation structure and plant phenology. Our results indicate that the use of a higher order closure turbulence scheme with multiple canopy layer representation is critical to land carbon cycle simulation. Based on our simulations, water vapor exchange between the land surface and the atmosphere is primarily through plant transpiration (78–88%), and canopy evapotranspiration is enhanced with the use of CN biogeochemistry. Our results indicate that the ratio of transpiration to evapotranspiration exhibits a two-stage variation pattern, and the transpiration fraction decreases in dense canopies.

1. Introduction

The physical processes in land surface control the lower boundary conditions for energy, water vapor and momentum in the lower atmosphere; therefore, a reasonable representation for these processes is crucial to regional and global climate simulations (Fatichi et al., 2015). Garratt (1993) reviewed the sensitivity of climate simulations to land surface treatments in different Global Climate Models (GCMs), and found that an appropriate land surface scheme is one major requirement for realistic global climate simulations. Such land surface schemes are necessary to properly represent the effects of soils and vegetation that are critical to terrestrial fluxes and climate simulations (Garratt, 1993; Sellers et al., 1997). In addition to biogeophysical impacts on climate simulations, Cox et al. (2000) demonstrated the importance of biogeochemical feedbacks on twenty-first century climate projections by incorporating a carbon cycle model into a fully coupled GCM. Based on their results, carbon cycle feedbacks could significantly accelerate climate change because the direct effect of CO_2 on photosynthesis rate saturates at higher CO_2 concentrations while a specific soil respiration rate continues to increase with temperature. The atmospheric CO_2 concentration was 250 ppmv higher in their fully coupled carbon simulation than in their uncoupled carbon simulation, resulting in a 1.5 K increase in global mean temperature when carbon cycle feedbacks were activated. Similar results were obtained in Friedlingstein et al. (2006) and Matthews et al. (2007).

However, the strength of carbon cycle feedbacks is regulated by the amount of available nutrients such as nitrogen in ecosystems, and the absence of an explicit treatment of nutrient dynamics in ecosystem simulations increases model uncertainties in the predictions of future atmospheric CO_2 concentration and the associated anthropogenic climate change (Thornton et al., 2009). Studies have shown that the inclusion of fully coupled carbon and nitrogen cycles in land surface schemes can reduce the simulated global terrestrial carbon uptake response to increasing atmospheric CO_2 concentration by 53–78%, relative to a carbon cycle only counterpart model (Thornton et al., 2007; Sokolov et al., 2008). Moreover, Thornton et al. (2007) concluded that

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the coupling of terrestrial carbon and nitrogen fundamentally impacts climate carbon cycle feedbacks, and the reduction of direct CO_2 fertilization effect cannot be reproduced by simple parameterizations of a carbon only model. Bonan and Levis (2010) quantified the effects of nitrogen dynamics on carbon exchange in the Community Land Model version 4 (CLM4) over the period 1973–2004. Their results suggested that the inclusion of nitrogen cycle would reduce both concentration-carbon feedback and climate-carbon feedback, compared with carbon only biogeochemistry. Several studies have also demonstrated the importance of terrestrial nitrogen feedbacks on the land carbon cycle (Sokolov et al., 2008; Thornton et al., 2009; Zaehle et al., 2010a; 2010b; Friedlingstein et al., 2014).

The effects of carbon-nitrogen (CN) biogeochemistry can also affect vegetation structure that is largely controlled by the trend of the land carbon cycle. Studies have found that changes in vegetation structures can influence the partitioning of latent and sensible heat fluxes and thus impact atmospheric boundary layer development (Foley et al., 2003; Fatichi et al., 2015). For example, stomatal conductance declines when atmospheric CO_2 concentration increases, leading to the reduction of evapotranspiration. This alters surface energy and water vapor fluxes, which in turn affects atmospheric circulation patterns and water cycle over land (Foley et al., 2003; Levis, 2010).

Apart from the impacts by CN biogeochemistry, recent studies have also found that the realism of model description of ecosystem structure and function in surface layer exchange processes is as important as the accuracy of other model physics (Weiss et al., 2012; Weiss et al., 2014; Chang et al., 2018). This is because the type and the density of vegetation control the states of surface, subsurface and atmospheric properties (Douville 2003; Dirmeyer and Zhao 2004), which largely affect ecosystem response and thus regulate local and regional scale climatic conditions (Arora, 2002; Pielke et al., 2011). Weiss et al. (2012) and Chang et al. (2018) have shown that a more realistic surface property description is beneficial to biogeophysical and biogeochemical simulations. However, their analyses did not consider the effects of CN biogeochemistry on the nonlinear interactions between canopy structure and turbulence transports.

This study aims to determine the effects of CN biogeochemistry on terrestrial fluxes, which are important to weather forecasts and climate simulations. In particular, we are interested in effects of CN biogeochemistry on the partitioning of evapotranspiration (ET) into evaporation and transpiration. We use a coupled model that integrates a prognostic canopy structure scheme based on CN biogeochemistry processes into a multiple canopy layer land surface model. More specifically, the CN biogeochemistry submodel in the commonly studied Community Land Model version 4.5 (CLM4.5) is coupled to the Advanced Canopy-Atmosphere-Soil Algorithm (ACASA) that uses carbon only biogeochemistry. ACASA simulates realistic turbulence transports by its third order closure parameterization, and CLM4.5 represents more advanced CN biogeochemistry with simpler turbulence parameterization. The resulting ACASA-CN model simulates fully coupled nonlinear terrestrial interactions with explicit plant traits representation, and it is the first model that uses a higher order closure parameterization and a vertically resolved canopy to represent feedbacks among vegetation structure, plant physiology, nutrient dynamics, and turbulence processes. The model incorporates detailed vertical canopy structural and functional representations, which is beneficial when analyzing the source of fluxes contributed by different parts of the simulated canopy, such as partitioning water vapor flux into evaporation from soil and canopy surfaces and transpiration from plant stomata.

Simulations across various types of ecosystem and microclimatic conditions were compared with remote sensing datasets and in-situ measurements in terms of canopy structure, energy, water vapor, and carbon fluxes. The effects of CN biogeochemistry on terrestrial fluxes simulation were investigated by conducting a series of offline simulations with carbon only biogeochemistry. We hypothesize that stomata controlled transpiration is regulated by the use of biogeochemistry, and the integration of realistic turbulence and advanced biogeochemistry schemes is beneficial to accurate land surface simulation. Continuous eddy covariance measurements were used to evaluate the energy, water vapor and carbon fluxes simulated by ACASA-CN. The amounts of evaporation and transpiration simulated by ACASA-CN using carbon only versus CN biogeochemistry were analyzed to test our hypothesis.

This paper is organized as follows. Section 2 introduces the numerical models and observational datasets used in this study. Simulation results and some relevant discussions are given in section 3. Model sensitivity and the effects of CN biogeochemistry are evaluated in section 4. Concluding remarks are provided in section 5.

2. Methods

2.1. CLM 4.5

The Community Land Model (CLM), which is the land surface component of the Community Earth System Model (CESM), is widely applied in regional and global climate simulations. CLM features a nested subgrid hierarchy, in which each grid cell can be composed of multiple land units, soil columns, and plant functional types (Oleson et al., 2013). This mosaic structure design enables it to efficiently represent complex land surface and subsurface patterns at a global scale. The vegetation canopy is represented by two leaf classes, one sunlit and the other shaded.

Major improvements were made to CLM version 4 (CLM4), including updates to soil hydrology, soil thermodynamics, the snow model, albedo parameters, the land surface types dataset, and the River Transport Model (Lawrence et al., 2011). Moreover, a carbon and nitrogen cycle model that includes prognostic vegetation phenology described in Thornton et al. (2002) and Thornton and Zimmermann (2007) was added to CLM4 to improve the biogeochemical processes in the model.

Several modifications were also applied to CLM version 4.5 (CLM4.5) to reduce the biases found in CLM4 and incorporate the latest scientific understanding of land surface processes (Oleson et al., 2013). The main canopy process modifications are as follows: (1) The use of a revised canopy radiation scheme, co-limitations on the photosynthesis rate, and revisions to the original photosynthetic parameters to fix the gross primary production biases found in CLM4 (Bonan et al., 2011; Bonan et al., 2012). (2) The application of temperature acclimation of photosynthesis, and improved stability of the iterative solution in the photosynthesis and stomatal conductance model (Sun et al., 2012). More detailed descriptions of the CLM4.5 can be found in Oleson et al. (2013).

2.2. ACASA-CN

The Advanced Canopy-Atmosphere-Soil Algorithm (ACASA) is a multiple canopy layer turbulence land surface model based on the diabatic third order closure method developed by Meyers and Paw U (1986; 1987). The multiple canopy layer and third order closure features enable ACASA to simulate realistic turbulent transports of energy, water vapor, momentum and carbon flux within and above vegetation canopies (Meyers and Paw U, 1986; Pyles et al., 2000; Pyles et al., 2004; Chang et al., 2018). ACASA includes nine sunlit leaf angle classes based on a spherical leaf distribution and one shaded leaf class, for each vertical layer. The default ten vertical canopy layers therefore produce 100 different leaf classes to detail canopy structural and functional properties. ACASA has been used to accurately simulate vertical microclimatic profiles within canopies and exchanges from land surfaces in a variety of ecosystems as a stand-alone diagnostic model (Meyers and Paw U et al., 1986; Pyles et al., 2000; Pyles et al., 2004; Staudt et al., 2010; Chang et al., 2018). It has been coupled with regional scale atmospheric models to realistically represent land surface