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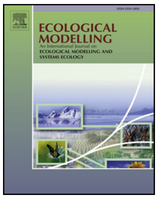

Using a spatially-distributed hydrologic biogeochemistry model with a nitrogen transport module to study the spatial variation of carbon processes in a Critical Zone Observatory

Yuning Shi[a,*], David M. Eissenstat[a], Yuting He[b], Kenneth J. Davis[b]

[a] *Department of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA, USA*
[b] *Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA, USA*

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ABSTRACT

Terrestrial carbon processes are affected by soil moisture, soil temperature, nitrogen availability and solar radiation, among other factors. Most of the current ecosystem biogeochemistry models represent one point in space, and have limited characterization of hydrologic processes. Therefore, these models can neither resolve the topographically driven spatial variability of water, energy, and nutrient, nor their effects on carbon processes. A spatially-distributed land surface hydrologic biogeochemistry model, Flux-PIHM-BGC, is developed by coupling the Biome-BGC model with a physically-based land surface hydrologic model, Flux-PIHM. In the coupled system, each Flux-PIHM model grid couples a 1-D Biome-BGC model. In addition, a topographic solar radiation module and an advection-driven nitrogen transport module are added to represent the impact of topography on nutrient transport and solar energy distribution. Because Flux-PIHM is able to simulate lateral groundwater flow and represent the land surface heterogeneities caused by topography, Flux-PIHM-BGC is capable of simulating the complex interaction among water, energy, nutrient, and carbon in time and space. The Flux-PIHM-BGC model is tested at the Susquehanna/Shale Hills Critical Zone Observatory. Model results show that distributions of carbon and nitrogen stocks and fluxes are strongly affected by topography and landscape position, and tree growth is nitrogen limited. The predicted aboveground and soil carbon distributions generally agree with the macro patterns observed. Although the model underestimates the spatial variation, the predicted watershed average values are close to the observations. The coupled Flux-PIHM-BGC model provides an important tool to study spatial variations in terrestrial carbon and nitrogen processes and their interactions with environmental factors, and to predict the spatial structure of the responses of ecosystems to climate change.

1. Introduction

The future of the Earth's climate is extremely sensitive to the changes in land surface (Friedlingstein et al., 2014) because of its ability to take up or emit large amounts of carbon dioxide and its impact on water and energy cycling. The terrestrial carbon cycle is a major contributor to uncertainties in future climate projections (Bodman et al., 2013). Terrestrial biogeochemistry models, which simulate ecosystem biogeochemical cycling of water, carbon, and nutrient, are therefore important in predicting the future of the Earth's climate, and have been included in the new generation of land models (i.e., the land components of Earth system models, or ESMs) and land surface models (e.g., Oleson et al., 2008; Niu et al., 2011).

Hydrologic processes have strong impacts on the terrestrial carbon cycle through their controls on photosynthesis, organic matter decomposition and nutrient transport (Rodriguez-Iturbe et al., 2001; Ju et al., 2006; Oleson et al., 2008; Lohse et al., 2009). Topographically driven lateral water flow and associated nutrient transport result in heterogeneously distributed soil water and nutrients availability, which lead to the spatial heterogeneity of land surface processes and biogeochemical processes. The description of hydrologic processes in terrestrial biogeochemistry models, however, is often highly simplified. Fisher et al. (2014) examined a total of 75 terrestrial biosphere models (TBMs), and indicated that most TBMs still use tipping or leaky bucket-based approaches for hydrology. Clark et al. (2015) reviewed hydrologic modeling advances in the land modeling community, and found that both upper (i.e., infiltration) and lower (i.e., recharge or subsurface runoff) boundary conditions for subsurface hydrology are highly simplified in those models, deep soil water or groundwater dynamics are usually neglected, and lateral flows are not explicitly accounted for. These models therefore have limited ability in representing the impact of hydrologic processes on biogeochemical processes. Clark et al.

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[*] Corresponding author.

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(2015) concluded that the development of land model can be improved by incorporating recent advances in hydrologic modeling. Improving the representation of hydrology will be one of the foci of TBM development over the next few years, as revealed by a survey to TBM developers (Fisher et al., 2014).

Terrestrial biogeochemistry models and land models usually use a one-dimensional model to represent the average carbon fluxes and stocks (i.e., quantities of carbon contained in carbon pools) over a large spatial area. Even if they can accurately estimate the average soil moisture and soil temperature over the large spatial area, estimating the spatial average of carbon fluxes and stocks is difficult since the interaction between hydrological processes and biogeochemical processes are nonlinear and each model grid is unique in sub-grid topography, soil texture, and land cover distributions. These models cannot represent the fine scale (e.g., 10^1–10^2 m) spatial variability in terrestrial carbon distribution, which can exceed the variability in magnitude of carbon stock and flux at larger scales (Houghton, 2005).

Coupling physically-based high-resolution spatially-distributed hydrologic models with terrestrial biogeochemistry models may yield improvements in terrestrial carbon cycle predictions (Yu et al., 2015). Recently there have been attempts to develop spatially-distributed ecohydrological models that contain physically based hydrologic components, or couple hydrologic models with land models or land surface models with biogeochemistry components, to improve the representation of hydrologic processes in biogeochemical modeling. Readers are referred to Fatichi et al. (2016) for a list of ecohydrological models.

Ivanov et al. (2008) coupled the Vegetation Generator for Interactive Evolution (VEGGIE) model to a spatially-distributed physically based hydrological model, the TIN-based Real-time Integrated Basin Simulator, tRIBS (Tucker et al., 2001). Fatichi et al. (2012) developed a spatially-distributed ecohydrological model, Tethys-Chloris. Nutrient dynamics (e.g., nitrogen dynamics) and soil thermodynamics, however, are neglected in both VEGGIE + tRIBS and Tethys-Chloris; thus, those models are likely to have difficulty simulating nutrient- or radiation-limited environments.

Niu et al. (2014) developed an integrated catchment-scale ecohydrological model by coupling a physically-based 3-D hydrological model, CATchment HYdrology (CATHY) (Camporese et al., 2010), to a land surface model with leaf dynamics, NoahMP (Niu et al., 2011). The coupled CATHY/NoahMP model has been calibrated and tested at two small first-order watersheds with high spatial resolution (10^0–10^1 m), and showed good ability in simulating surface energy and water fluxes. The simulated watershed average CO_2 fluxes in spring, however, did not compare well with the observations, due to the lack of soil carbon processes in the NoahMP model.

Tague and Band (2004) developed a semi-distributed ecohydrological model, the Regional Hydro-Ecological Simulation System (RHESSys), which has been used in a number of ecohydrological studies. Shen et al. (2013) coupled a process-based quasi-3-D hydrologic model, Process-based Adaptive Watershed Simulator (PAWS) (Shen and Phanikumar, 2010), to the Community Land Model (CLM) (Oleson et al., 2010), and used the coupled PAWS + CLM model to study the impact of hydrologic processes on land surface and carbon dynamics (Shen et al., 2016). Kollet and Maxwell (2008) and Shrestha et al. (2014) coupled a three-dimensional variably saturated groundwater flow model, Parallel Flow (ParFlow) (Kollet and Maxwell, 2006) to CLM, and the coupled model has recently been applied at continental scale (Maxwell et al., 2015). Although lateral water flow is simulated in RHESSys, PAWS + CLM and CLM-ParFlow, nutrient transport with lateral water flow is not accounted for; RHESSys does not simulate surface energy balance or soil thermodynamics. In addition, none of the above models, except for Thehys-Chloris, simulates topographic solar radiation, which is an important factor in determining the spatial patterns of forest carbon dynamics (Smith et al., 2017) and other critical zone processes (Pelletier et al., 2018). There are also reactive solute transport models, e.g., the Unsaturated-Zone Flow-Reactive Transport in 3 Dimensions (UZF-RT3D; Bailey et al., 2013, 2015) model, that include the simulation of carbon and nitrogen cycling in the soil-plant system. These models, however, usually ignore or have highly simplified descriptions of aboveground processes.

A high-resolution, spatially-distributed, coupled hydrologic-land surface-terrestrial biogeochemistry model with nutrient transport simulation, which can reflect the impact of soil water, soil temperature, topographic solar radiation, and nutrient availability on ecosystem carbon processes, remains elusive to date. In addition, those spatially-distributed models are usually evaluated using watershed average measurements. The spatial patterns of carbon stocks and fluxes are often excluded from evaluation.

In this study, a coupled land surface hydrologic terrestrial biogeochemistry modeling system is developed by coupling the Penn State Integrated Hydrologic Model with a surface heat flux module (Flux-PIHM) (Shi et al., 2013) to the Biome-BGC model (Thornton et al., 2002). Flux-PIHM is a coupled land surface hydrologic model, which incorporates the Noah land surface model (Chen and Dudhia, 2001; Ek et al., 2003) into the Penn State Integrated Hydrologic Model (PIHM) (Qu and Duffy, 2007), a physically based spatially-distributed hydrologic model. Flux-PIHM has fully coupled surface and subsurface flow, lateral surface and subsurface water flow, macropore flow, and fully explicit river flow. The simulation of those processes has been identified as the key candidate areas to improve the hydrologic processes in land models by Clark et al. (2015). Flux-PIHM is able to represent the link between groundwater and the surface energy balance, as well as the land surface heterogeneities caused by topography at high spatial resolution (Shi et al., 2015a). This model is therefore an ideal candidate to improve the representation of hydrologic processes in TBMs. Biome-BGC is a process-based mechanistic terrestrial biogeochemistry model, and is the prototype of the carbon-nitrogen (CN) model in the CLM.

Past research has focused largely on the spatial variations of carbon processes with respect to precipitation, air temperature, nitrogen deposition, land cover, and land use (Raich and Schlesinger, 1992; Jobbágy and Jackson, 2000; Houghton, 2005). The Shale Hills watershed (0.08 km^2) is relatively homogeneous with respect to these properties, and enables study of the impact of additional processes including topography, watershed hydrology, soil physical properties and shading on the carbon cycle of a first-order watershed. We also note that low-order watersheds cover a large fraction of the landscape (Shreve, 1969; Benda et al., 2005). Therefore, we test the coupled model at the Shale Hills watershed, a first-order, monolithologic, forested watershed. The watershed is located in central Pennsylvania, and is one of the experimental sites of the Susquehanna Shale Hills Critical Zone Observatory (SSHCZO). The broad array of hydrological, land surface, and biogeochemical observations, including discharge, soil moisture, soil temperature, meteorological conditions, above ground carbon stocks and productivity, soil carbon stocks, leaf area index (LAI) and catchment-scale net ecosystem-atmosphere carbon fluxes, makes the Shale Hills watershed an ideal site for the coupled model test. The predicted spatial patterns of carbon stocks are evaluated using field measurements. We also examine the spatial patterns of carbon fluxes, as well as investigate the interaction of abiotic factors with vegetation carbon.

2. Description of the coupled modeling system

2.1. The Penn State Integrated Hydrologic Model with a surface heat flux module

The Penn State Integrated Hydrologic model with a surface heat flux module (Flux-PIHM) (Shi et al., 2013) is a coupled land surface hydrologic model. In Flux-PIHM, the land surface is decomposed into unstructured triangular grids and river channels are represented by rectangular elements. Channel flow and surface water flow calculations are handled by PIHM, using the 1-D (channel flow) and 2-D (surface