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Effects of fine-scale soil moisture and canopy heterogeneity on energy and water fluxes in a northern temperate mixed forest

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ABSTRACT

Coupling between soil moisture, vegetation biomass, and energy fluxes is characterized by nonlinearities and thus current land surface parameterizations with aggregated surface response may produce biased results. This study aims to improve the understanding of the coupling modes between fine-, tree-scale (few meters) canopy and soil moisture variations, and their impacts on spatially integrated energy and water fluxes. The study was carried out for a spatially heterogeneous, temperate mixed forest environment of Northern Michigan located near the University of Michigan Biological Station. A high-resolution, physically-based ecohydrological model (tRIBS + VEGGIE) was used as a data integration tool to upscale spatial heterogeneities resolved at a tree-scale to a coarse-scale (several kilometers). Several simulation cases involving tree-scale variations in initial soil moisture, leaf area, and radiative forcing were designed. In order to infer the effects of coarse-scale aggregation, a *lumped* case representing the commonly used spatially-lumped representation was also simulated. The results demonstrate that heterogeneous canopy biomass determines the spatial dynamics of soil moisture. The spatial distribution of canopy height may play a particularly important role in determining the domain-scale fluxes when a forest system is in moisture-limiting conditions. Specifically, the tree-scale effects on light exposure and shading result in smaller spatially aggregated transpiration and lower water stress as compared to the results of the lumped representation.

1. Introduction

Vital land-surface characteristics such as soil moisture and canopy biomass exhibit a high degree of heterogeneity at different scales, resulting in spatially varying energy and water exchanges between the land-surface and the atmosphere (Anderson et al., 2003; Brunsell and Gillies, 2003; Fatichi et al., 2012b; Raupach and Finnigan, 1995; Ryu and Famiglietti, 2006; Salmun and Molod, 2006). The current generation of land surface models considers spatial heterogeneity at a scale of a few kilometers and lumps characteristics of finer scales using the “*big-leaf*” or “*patch-mosaic*” schemes that represent surface cover as aggregated patches with uniform properties (Avissar and Pielke, 1989; Koster and Suarez, 1992; Pappas et al., 2013; Sellers et al., 1996; Seth et al., 1994; Sridhar et al., 2003; Walko et al., 2000). However, the coarse grid/patch resolutions and simplified parameterizations of subgrid-scale heterogeneity may result in errors to the modeled mean water and energy fluxes due to the strong nonlinearity and fine-scale heterogeneity of land surface processes (Atchley and Maxwell, 2011; Avissar and Schmidt, 1998; Brunsell et al., 2011; El Maayar and Chen, 2006; Hu et al., 1999; Maxwell et al., 2007; Rowe, 1993; Sellers et al., 2007; Wood et al., 2011; Yates et al., 2003).

In particular, the aggregation of spatially varying soil moisture in a coarsely resolved grid may obscure the spatial extent of subgrid areas where soil moisture is limiting for plants and thus lead to an inaccurate prediction of grid-scale latent heat flux (Ronda et al., 2002; Sellers et al., 2007). For example, during dry intervals, when averaged soil water content over a large fraction of an area approaches the wilting point and transpiration become moisture-limited, wetter regions that are not stressed may exist because of vegetation variability, topographic shading, or regions of groundwater discharge. Lumping soil moisture over a coarsely resolved grid would theoretically lead to an underestimated grid-scale evapotranspiration. Overall, the impact of aggregating subgrid

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soil moisture variability on the predicted coarse-scale energy flux depends on the grid cell size as well as time- and scale-dependent properties of soil moisture fields such as the mean and variance (Crow and Wood, 2002).

For a vegetated land surface, the spatial mean and variance of soil moisture can be correlated with the spatial variability of vegetation biomass, as the canopy influences soil water content at very fine spatial scales through the processes of interception of precipitation and transpiration uptake of moisture. The canopy is characterized by a three-dimensional (3-D) structure of spatially varying attributes such as leaf density, leaf area index (LAI), leaf optical properties, tree heights and canopy gaps. The effects of spatially distributed LAI or reflective properties have been well recognized in studies of land surface models (Li and Avissar, 1994; Sellers et al., 1995). The aggregated latent heat simulated by considering sub-grid variable LAI could be either larger or smaller than the domain-scale latent heat simulated with spatially lumped LAI, depending on different vegetation types (El Maayar and Chen, 2006). The 3-D structure of canopies results in complex light regimes leading to different absorption of energy even when crowns have the same exposure to light (Chen et al., 2000; Deutschman et al., 1999; Knyazikhin et al., 1997; Song et al., 2009; Yang and Friedl, 2003). Further, within each crown, the partition of available energy into transpiration and sensible heat flux depends on nonlinear responses of leaf stomata and photosynthesis to moisture and light availability (Law et al., 2001; Pieruschka et al., 2010). Models considered heterogeneous radiation environment might generate less latent heat than that of models with spatially uniform radiation environment (Knyazikhin et al., 1997; Song et al., 2009).

The main objective of this study is to explore the degree to which the spatial structure of vegetation characteristics is important for determining the magnitude and spatial variation of soil moisture and evapotranspiration. We hypothesize that fine-scale heterogeneous canopy interacts with spatially variable soil moisture and regulates domain-scale transpiration. The study addresses this hypothesis by (1) explicitly representing spatially varying vegetation biomass and soil moisture at a tree scale in a numerical model and; (2) examining the differences in the estimates of spatially integrated energy and water fluxes obtained with fine-scale representations vs. a commonly used spatially-lumped representation; and (3) presenting an approach to consider tree-scale heterogeneity of radiation and assessing its role in estimating domain-scale transpiration.

2. Study site and observational data

2.1. Topography and vegetation

The study location is a temperate mixed forest near the UMBS in Northern Michigan, U.S.A. (45.56°N, 84.71°W). This northern hardwood forest represents a transitional zone between mid-latitude hardwood and boreal forests (Schmid et al., 2000). The area is a gently sloping outwash plain with an average elevation of ∼300 m and a range of ∼20 m (Pressley et al., 2005). The forest has a mean overall stand density of 1012 [stems ha^{-1}], while the stand density for trees with the diameter at breast height (DBH) larger than 20 cm is 281 [stems ha^{-1}] (Garrity et al., 2012). Currently, the forest is dominated by aspen (*Populus grandidentata*), other species include red oak (*Quercus rubra*), maple (*Acer rubrum, Acer saccharum*), birch (*Betula papyrifera*), and pine (*Pinus strobus, Pinus resinosa*) (Bovard et al., 2005; Schmid et al., 2003). Field data collected at the UMBS forest (Gough et al., 2007, 2008) shows the fine root biomass decays exponentially with depth and that 95% of the biomass is concentrated within the top 80 cm of the soil (He et al., 2013). Yearly growing season start and end dates were determined following the methods of Schmid et al. (2003).

2.2. Meteorological data and energy fluxes

Meteorological variables and energy fluxes in the UMBS forest have been monitored at the AmeriFlux eddy-covariance tower since 1999 (Schmid et al., 2000), including wind speed, wind direction, frictional velocity, air and soil temperature, atmospheric pressure, water vapor pressure, downwelling and upwelling shortwave and longwave radiation, net radiation, photosynthetic active radiation, latent, sensible, and ground heat fluxes. Meteorological data processing and analysis follows that used by Nave et al. (2011). Specifically, the latent heat was obtained by eddy covariance measurements of water vapor concentrations using closed-path infrared gas analyzers (LI-6262 and LI-7000, LI-COR Inc., Nebraska, U.S.A.). Additionally, precipitation is recorded with a Belfort weighing rain gauge (Rainfall Transmitter series 5915-6, Belfort Instrument Co., Baltimore, U.S.A.) located in an open field near the AmeriFlux tower (45.56°N, 84.68°W; the UMBS NADP/NTN monitoring site MI09, http://nadp.sws.uiuc.edu/).

2.3. Soil moisture

Soils are dominated by well-drained spodosols: 92% sand, 7% silt, and 1% clay; and the soil properties were observed to be fairly uniform over the study site. Two well drilling records for a location in the immediate vicinity of the AmeriFlux tower show that the water table is at a depth of 20 m during middle of a growing season. Soil moisture data has been collected in two soil pits near the AmeriFlux tower with a half-hourly resolution since April 2009 (He et al., 2013). Soil moisture probes (Hydra probe SDI-12, Stevens Water Monitoring Systems, Inc., Portland, U.S.A.) were deployed at each of the following depths: 5, 15, 30, 60, 100, 200, and 300 cm. As further evidence of a deep water table, the observed volumetric moisture contents at 300 cm were smaller than 0.08 [$m^3\ m^{-3}$] or near the residual content (∼0.04 [$m^3\ m^{-3}$]) over most of the period of observation.

Soil moisture has also been sampled within a 0.25 ha area near the AmeriFlux tower along six 50-m long transects at 2-m intervals (He et al., 2013). These measurements represent averaged moisture contents over the top 20 cm layers. Data was collected at roughly monthly intervals during the 2010 growing season.

3. Model and simulation configuration

3.1. tRIBS + VEGGIE overview

The tRIBS + VEGGIE model is a spatially distributed, high-resolution, ecohydrological model that represents the essential water and energy processes over a basin and links them to plant life regulatory processes (Ivanov et al., 2008a,b). The processes represented include interception, evapotranspiration, surface energy balance, infiltration, snow hydrology, groundwater, runoff, and overland or channel flow. The model represents the spatio-temporal variability of key variables at fine scales (5–100 m), and resolves hydrologic processes at a high temporal resolution ranging from minutes to hours. Because of the model's flexibility and the capability of simulating detailed hydrologic processes, it has been applied to watersheds in various hydrological or vegetation settings (Flores et al., 2009; Ivanov et al., 2008b, 2010).

In the original formulation of tRIBS + VEGGIE, spatial variations of shortwave radiation incident on a unit surface of vegetated area are introduced only in the presence of topography; this irradiance will be referred to as "above-canopy" radiation hereafter.