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Canopy profile sensitivity on surface layer simulations evaluated by a multiple canopy layer higher order closure land surface model

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A B S T R A C T

The canopy structural and functional impacts on land surface modeling of energy and carbon fluxes were investigated by a series of simulations conducted at AmeriFlux eddy covariance sites. Canopy structures were described by different degrees of complexity of Leaf Area Index (LAI) datasets. The monthly climatological LAI datasets applied in the Weather Research and Forecasting (WRF) Model and the Community Earth System Model (CESM) were used to represent static ecological conditions. The LAI remotely sensed by the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to represent time-varying ecological conditions with natural variability. To investigate the sensitivity of different canopy profile representations, all of these LAI datasets were used to assign the necessary ecological information for single and multiple canopy layer land surface models to simulate a seven-year period across a variety of vegetation covers. The results show that a more realistic canopy profile representation (i.e., multiple layers), both in terms of structural and functional treatments, improves biogeophysical and biogeochemical simulations. The root mean square errors for the simulated evapotranspiration and Net Ecosystem Exchange are reduced by 10% and 15%, respectively when the ecological information is represented by a more realistic time-varying LAI dataset instead of a static LAI dataset with no geographical sensitivity. A land surface model with multiple canopy layers and a realistic ecological dataset, which can better represent ecosystem structural and functional responses to microclimate conditions, is thus recommended for long-term climate projections.

1. Introduction

The terrestrial carbon sink accounts for more than one third of the annual global carbon sink in the atmosphere by plant photosynthetic carbon assimilation (Farquhar et al., 1993; Ciais et al., 1997; Sitch et al., 2003). Although the total terrestrial carbon sink is smaller than the oceanic carbon sink, the terrestrial carbon sink exhibits more variability in both space and time due to the more complex vegetation distribution and more prominent seasonality. This type of variability over land can be captured by implementing realistic vegetation type distribution and seasonal leaf area variation in land surface models (Bonan et al., 2002). Ecosystem response is dependent on ecophysiological processes that are strongly plant type and leaf area dependent (Gifford, 1974; Ball et al., 1987; Collatz et al., 1992, Mahowald et al., 2016). The plant species communities and the leaf area are usually represented by simplified representative ecosystems labeled as Plant Functional Types (PFT) each with a characteristic Leaf Area Index (LAI) (Bonan et al., 2002). Although PFTs are essential in determining ecosystem response mechanisms (Bunn and Goetz, 2006), they are usually assumed to be phenologically constant in surface vegetation datasets, that is the PFTs do not exhibit regular seasonal variations for the same geographical location. Seasonal variations in LAI is often prescribed in surface vegetation datasets, and LAI has been suggested to be one of the most important variables in global terrestrial carbon simulation due to its significant impacts on plant physiological and phenological processes (Murray-Tortarolo et al., 2013; Anav et al., 2013; Hardwick et al., 2015). Previous works on Amazon's deforestation highlighted the impacts from LAI changes on ecosystem responses through shifting the energy partition from available energy into sensible and latent heat fluxes and thus affecting atmospheric boundary layer development and local and regional circulation patterns (Foley et al., 2003; Knox et al., 2011; Fatichi et al., 2015). As a result, a more realistic high-resolution surface vegetation LAI dataset, such as those available from satellite observations (Carlson and Ripley, 1997; Yang et al., 2006), is expected to improve global terrestrial carbon simulation (Zhang et al., 2003 and Garrity et al., 2011).

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Table 1
The AmeriFlux sites investigated in this study.

Site name	Vegetation type (IGBP)	Predominant species	Coordinates
Blodgett Forest (US-Blo)	Evergreen needleleaf Forest	Ponderosa pine	38.8952°N, 120.6327°W
Duke Forest Loblolly Pine (US-Dk3)	Evergreen needleleaf Forest	Loblolly pine	35.9782°N, 79.0942°W
Harvard Forest (US-Ha1)	Deciduous broadleaf	Red oak, red maple, black birch, white pine, and hemlock	42.5378°N, 72.1715°W
Howland Forest Main (US-Ho1)	Evergreen needleleaf Forest	Red spruce, and eastern hemlock	45.2041°N, 68.7402°W
Vaira Ranch (US-Var)	Grasslands	Purple false brome, smooth cat's ear, and rose clover	38.4067°N, 120.9507°W
Wind River Field Station (US-Wrc)	Evergreen needleleaf Forest	Douglas fir, and western hemlock	45.8205°N, 121.9519°W

Global surface vegetation datasets based on remotely sensed observations have been applied in models such as the Weather Research and Forecasting Model (WRF) and the Community Earth System Model (CESM) to improve surface layer simulation (Myneni et al., 2002; Myneni et al., 2003; Lawrence and Chase, 2007; Subin et al., 2011). However, the default settings in these models, to increase computational efficiency, only employ the monthly climatology global surface vegetation information to capture the general global vegetation distribution, and thus gloss over higher frequency LAI variations in space and time. This relatively static vegetation distribution approach comes with some uncertainties from inappropriate vegetation descriptions in long-term climate simulations (Levis et al., 2000; Diffenbaugh, 2005; Alo and Wang, 2010; Jeong et al., 2011; Yin et al., 2016). Recent studies, with single canopy layer models, have shown that more realistic LAI datasets are able to improve surface flux simulation and the predictions of drought conditions (Leuning et al., 2008; Ford and Quiring, 2013; Kumar et al., 2014; Hardwick et al., 2015). The realism of LAI datasets can have even stronger impacts in multiple canopy layer land surface models because the more sophisticated schemes could be more sensitive to real time canopy structure descriptions (Baldocchi and Wilson 2001; Ryder et al., 2016).

So far, few studies have discussed the sensitivity of multiple vertical canopy layer representations to turbulence fluxes simulation (Baldocchi and Wilson 2001; Kucharik et al., 2006; Ryder et al., 2016), and none of them employed higher order closure methods to accurately represent non-local turbulent transport that occurs in vegetated canopies.

In this study, we used a multiple canopy layer, higher order closure turbulent transfer model with detailed leaf physiology modules to investigate ecosystem response to natural canopy structural variations, driven by AmeriFlux site data. The site level scale was chosen to allow direct comparison between field measurements and model simulations. We proposed two hypotheses: (1) the temporal realism of canopy structural representation (mainly live LAI) is critical to land surface simulation; and (2) the realism of canopy functional parameterization is equally important. These hypotheses are linked to several different questions: How important are accurate turbulent parameterizations to overall fluxes? How important are multiple layers to fluxes? And, how important are the vertical profiles of scalars, with their potential to change ecophysiological response in each layer, to the overall fluxes? To examine hypothesis (1), we conducted a series of simulations with different descriptions of LAIs, e.g., more realistic time varying LAI versus static LAI datasets, at six AmeriFlux eddy covariance sites encompassing grassland, evergreen needleleaf forest and deciduous broadleaf forest across the continental United States. We examined hypothesis (2) by comparing the simulation results from land surface models with different levels of complexity in canopy process parameterization. These models ranged from a commonly used single layer land surface model with flux-gradient turbulent transfer physics, to a single layer canopy with higher order closure turbulence physics, to the end point in complexity of a multiple layer model with higher order closure turbulence physics. In all cases, the simulation results were then compared with AmeriFlux eddy covariance field measurements to test our hypotheses. The details of the models used in this study are given in Section 2, and descriptions of the six AmeriFlux sites and the chosen LAI datasets are given in Section 3. The simulation results and comparison to eddy covariance measurements are shown in Section 4, followed by discussion of results in Section 5, and ending in some concluding remarks.

2. Data

2.1. The AmeriFlux network, quality control and sites chosen

The AmeriFlux network was launched in 1996 to establish a dataset for carbon, water and energy fluxes in major climate and ecological biomes in North and South America based on eddy covariance measurements, with quality control and standardized data formats (Baldocchi et al., 2001). In this study, a range of microclimate and vegetation types were sampled by selecting six AmeriFlux sites across the continental United States, including four evergreen needleleaf forest sites, one broadleaf forest site and one C3 grassland site (Sections 2.1.1–2.1.6; Table 1), for the years 2000–2006. This time period was chosen to match the maximum available continuous data periods of the remotely sensed LAI by the Moderate Resolution Imaging Spectroradiometer (MODIS), and the meteorological and biological datasets at the six AmeriFlux sites.

Three quality control criteria were applied to the AmeriFlux network data. Data were omitted when (1) there was a rainfall event before or during the data collection period, which could have adversely affected sensor accuracy; (2) the observed frictional velocity was lower than 0.1 m/s (Reichstein et al., 2005), suggesting weak turbulence conditions in which two major problems could occur: (a) the eddy-covariance method might not accurately measure energy and carbon fluxes, and (b) fast response sonic anemometers could yield reduced accuracy, partially because of spatial resolution in their averaging volumes; and (3) the measured energy fluxes did not meet the energy balance closure criteria defined as the sum of sensible and latent energy within 20 percent error of the observed available energy, suggesting that there were potentially large errors associated with eddy covariance and/or net radiation and heat storage measurements. The philosophically supported use of the turbulent kinetic energy velocity scale or the standard deviation of the vertical wind velocity for indicating low turbulence regimes (Wharton et al., 2009) was not used because these measurements are not routinely available for the AmeriFlux sites. A brief description for the six AmeriFlux sites (Blodgett Forest, Duke Loblolly Pine Forest, Harvard Forest, Howland Forest, Wind River Forest, and Vaira Ranch Grassland) is given in the following paragraphs, and more detailed descriptions can be found on the AmeriFlux website (http://ameriflux.lbl.gov/).

2.1.1. Blodgett forest (USBlo)

The Blodgett Forest site (Goldstein et al., 2000) is located in El Dorado County, California, USA (38.8952°N, 120.6327°W). This site consisted of a mixed evergreen needleleaf forest dominated by ponderosa pine in a Mediterranean climate. The canopy height was 4 m when established in May 1997 with a growth rate of approximately 0.5 m/yr. The tower height was 10.5 m before February 2003 and changed to 12.5 m after that.