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Modeling temperature and humidity profiles within forest canopies

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ABSTRACT

Physically-based models are a powerful tool to help understand interactions of vegetation, atmospheric dynamics, and hydrology, and to test hypotheses regarding the effects of land cover, management, hydrometeorology, and climate variability on ecosystem processes. The purpose of this paper is to evaluate recent modifications and further refinements to a multi-layer plant canopy model for simulating temperature and water vapor within three diverse forest canopies: a 4.5-m tall aspen thicket, a 15-m tall aspen canopy, and a 60-m tall Douglas fir canopy. Performance of the model was strongly related to source strength and profile stability within the canopy. Root mean square deviation (RMSD) between simulated and observed values tended to be higher for the summer periods when there was much more heat and vapor added to the canopy space due to solar warming and transpiration. Conversely, RMSD for vapor pressure was lowest for the winter periods when vapor additions within the canopy space were minimal. RMSD for temperature ranged from 0.1 °C for the top of the 15-m aspen canopy during the winter to 1.6 °C for the bottom of the 4.5-m aspen thicket during the summer period. RMSD for vapor pressure ranged from 0.002 kPa for the top of the 15-m aspen canopy during winter to 0.141 kPa for the bottom of the 4.5-m aspen thicket during the summer. Unstable profile conditions were simulated better by the model than stable conditions for all sites. RMSD for temperature at the bottom of the 4.5-m aspen, 15-m aspen and 60-m Douglas fir were 0.89, 0.77, and 0.85 °C, respectively, for unstable conditions compared to 1.44, 0.89 and 1.16 °C for stable conditions. Stable profiles are more challenging to accurately simulate because dispersion within a stable profile is lower thereby creating larger gradients. Temperature differences between the bottom and above canopy sensors were within 3 °C for unstable conditions for all sites, but were as much as −10 °C under stable conditions. The model exhibited the greatest discrepancies relative to measurements in the 4.5-m aspen thicket under stable conditions, likely due to horizontal ejections from this relatively small patch of vegetation that could not be addressed by the one-dimensional model. At each site, the model performed best near the top of canopy where the air was well mixed and gradients between it the meteorological conditions above the canopy used to force the model were minimal.

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1. Introduction

The transport of mass and energy in plant environments is of great interest due to concerns regarding the effects of climate on vegetation and the influence of management on their ecosystems. The exchange of momentum and scalars within and above forest canopies is a key part of these ecosystems. The forest canopy strongly influences these fluxes and impacts the energy balance and microclimate within the plant canopy (Monteith, 1975; Norman, 1979; Baldocchi et al., 2002; etc.). Physically-based models are a powerful tool to help understand interactions of vegetation, weather, and hydrology, and to test hypotheses regarding the effects of land cover, management, and climate variability on ecosystem processes.

Combining intensive field measurements with model simulations helps to extend knowledge of fluxes controlling metabolic processes within plant canopies while elucidating gaps in understanding. Several studies have combined intensive field measurements with simulations from multi-layer canopy models, but typically covered relatively short periods of time and usually only one canopy profile. Wohlfahrt (2004) used eddy covariance (EC) measurements to compare 4 days of modeled fluxes and concentrations within and above a mountain meadow canopy for different Lagrangian models and parameterization schemes. Haverd et al.

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(2009) used above-canopy EC measurements and within canopy chamber measurements from a two-week campaign in combination with a SVAT (soil–vegetation–atmosphere transfer) model to determine vertical profiles of the Lagrangian time scale that optimized agreement between measured and modeled temperature, vapor, and carbon dioxide profiles. Pyles et al. (2000) compared surface fluxes from the ACASA model based on third-order turbulence closure with comprehensive observations from six diverse sites for up to 88 days. Staudt et al. (2011) used a combination of the ACASA model, the three-dimensional microclimate and gas exchange model STANDFLUX, and 8 days of ET and sap flux measurements to quantify the vertical structure of canopy evapotranspiration of a Norway spruce forest. Baldocchi et al. (2002) used the biophysical model CANOAK to evaluate the effects of leaf characteristics, vertical variations in leaf area, photosynthetic capacity, and weather on CO_2, water vapor, and sensible heat exchange, but no comparisons were made with measured values. Dufrêne et al. (2005) developed the multi-layer net ecosystem exchange model CASTANEA and compared it with EC measured carbon and water fluxes from a beech forest for an entire year, but no within-canopy comparisons were conducted. Thus, long-term assessments of multi-layer models for simulating within-canopy scalars at multiple sites are lacking. Such assessments that span a range of seasonal conditions are particularly needed to encompass periods with different boundary-layer atmospheric stability and source strength conditions to indicate the degree of accuracy afforded by relatively simple models for different canopy and meteorological conditions.

The Simultaneous Heat and Water (SHAW) model originally developed by Flerchinger and Saxton (1989) and modified by Flerchinger and Pierson (1991) to include a plant canopy has been widely tested for a variety of applications. Its ability to simulate heat, water and chemical movement through plant cover, snow, residue and soil for predicting climate and management effects on evaporation, transpiration, energy fluxes, soil water, soil freezing, snowmelt, soil temperature, and surface temperature has been demonstrated (Flerchinger et al., 1996, 1998; Flerchinger and Seyfried, 2014; Parkin et al., 1999; Hymer et al., 2000; Nassar et al., 2000; McDonald, 2002; Preston and McBride, (2004); Masin et al., 2005; Fallow et al., 2007; Chauvin et al., 2011, etc.). Improvements to the model for within-canopy processes were reported by Flerchinger et al. (2009, 2012). Flerchinger et al. (2012) assessed different approaches for simulating mass and energy fluxes through plant canopies by comparing simulations from the model with detailed flux measurements above and below an aspen canopy. As a result of their study, Lagrangian far field turbulent transfer was incorporated into the model, as well as provisions for computing wind profile parameters for sparse plant canopies. However, the study focused primarily on energy fluxes and did very little to evaluate simulated scalar profiles within the plant canopy. Therefore, the primary purpose of this paper is to evaluate the model for simulating temperature and water vapor scalars within three diverse forest canopies in terms of species, stand height, and density over the course of a year when processes controlling mass, energy, and momentum fluxes differ in terms of importance. Although previous versions of the model have been applied at each of the three sites, a comprehensive evaluation of canopy scalar profiles was not performed. A secondary objective is to present minor refinements for sparse canopies to the modifications of Flerchinger et al. (2012)

2. Model description

The SHAW model has been tested and applied extensively over a range of vegetation types and environments. It was developed with sufficient detail to be relevant for a range of applications, it is physically based making it applicable to a wide range of systems, and yet it is simple and computationally efficient for ease of use. The system described by the model illustrated in Fig. 1 consists of a vertical, one-dimensional profile that includes a vegetation canopy, snow cover, plant residue, and the soil profile. Weather conditions above the upper boundary and soil conditions at the lower boundary (e.g. gravity drainage or specified soil water content and temperature) define heat and water fluxes into the system. A layered system is established through the model domain, with each layer represented by a node. The surface energy balance in the SHAW model includes short and long-wave radiation absorbed, transmitted and reflected by multiple canopy layers, and sensible and latent heat transfer at the exchange surface for the top layer of the canopy, snow, residue or soil. Full solution of the surface energy balance at the upper boundary is solved iteratively with the interrelated heat, liquid water, and vapor fluxes between layers down through the profile using implicit finite-difference equations.

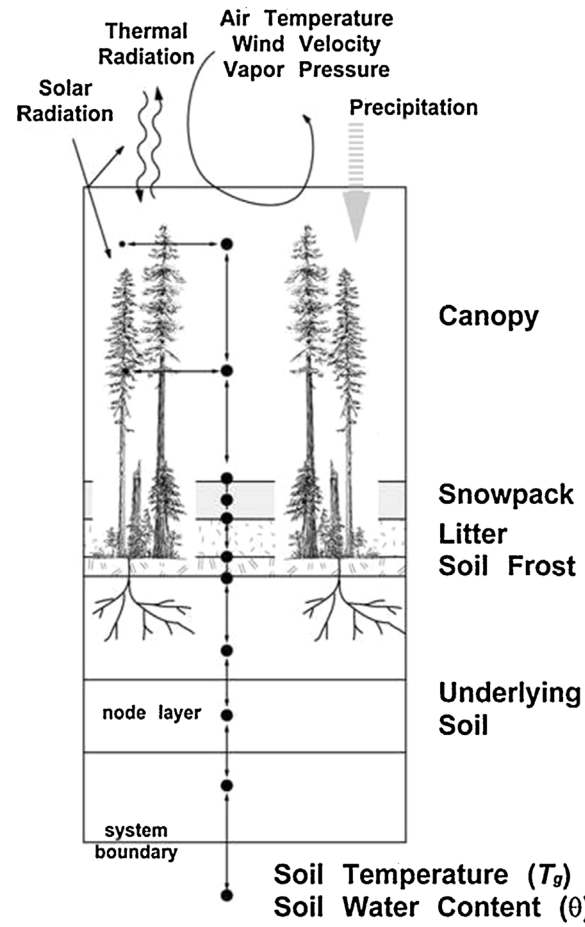

Fig. 1. Conceptual diagram of the physical system described by the SHAW model.

The model simulates the surface energy balance, evapotranspiration and fluxes within a multi-species plant canopy using detailed physics of heat and water transfer through the soil–plant–atmosphere continuum. The canopy is typically divided into layers with <0.5 leaf area index within each layer, or as specified by the user. Source terms for heat and vapor within each canopy layer i are computed from the leaf energy balance for each plant species j (Flerchinger et al., 1998), expressed as:

$$S_{n,i,j} + L_{n,i,j} + 2L_{Al,i,j}\rho_a c_a \frac{\left(T_{a,i} - T_{l,i,j}\right)}{r_{h,i,j}} - 2L_{Al,i,j}L_v \frac{\rho_{va,i} - \rho_{vs,i,j}}{r_{v,i,j} + r_{s,i,j}} = m_{c,i,j}c_{c,i,j}\frac{\delta T_{l,i,j}}{\delta t}. \quad (1)$$