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A coupled 1-D atmosphere and 3-D canopy radiative transfer model for canopy reflectance, light environment, and photosynthesis simulation in a heterogeneous landscape

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Abstract

Detailed knowledge of light interactions between the atmosphere and vegetation, and within vegetation are of particular interest for terrestrial carbon cycle studies and optical remote sensing. This study describes a model for 3-D canopy radiative transfer that is directly coupled with an atmospheric radiative transfer model (Forest Light Environmental Simulator, FLiES). The model was developed based on the Monte Carlo ray-tracing method using some existing modeling frameworks. To integrate the canopy radiative transfer model with atmosphere, the same numerical method, sampling technique, and variance reduction technique were employed in both the atmospheric and the canopy modules. Farquhar's leaf photosynthesis model was combined to calculate the canopy level photosynthesis from the light environmental parameters obtained by the radiative transfer calculation. In order to document the quality of the coupled model, we first compared the atmospheric radiative transfer module to well known 1-D atmospheric radiative transfer models, and then evaluated the 3-D canopy radiative transfer module against a series of test cases provided by the RAMI On-line Model Checker (ROMC). We used the model to show the impact of atmospheric properties and 3-D canopy structure on the directionality of downward photosynthetically active radiation (PAR) at the top of canopy, the 3-D distribution of absorbed PAR (APAR), and overall canopy photosynthesis. The results indicate the importance to consider angular geometry of incident light at TOC and 3-D canopy structure.

Keywords: 3-D canopy radiative transfer; Canopy reflectance; Photosynthetically active radiation; Monte Carlo method

1. Introduction

Detailed information of light interactions between atmosphere and vegetation, and within vegetation are of particular interest for terrestrial carbon cycle studies and optical remote sensing. Recent studies have shown that changes in the atmospheric radiation regime due to aerosols and clouds affect canopy photosynthesis (e.g., Chameides et al., 1999; Cohan et al., 2002; Gu et al., 2003; Kobayashi et al., 2005; Nemani et al., 2003; Niyogi et al., 2004; Roderick et al., 2001). An increase/decrease in canopy photosynthesis and its degree, however, largely depends on atmospheric conditions and canopy structure. A mechanistic understanding is necessary to generalize the effect of the radiation regime on canopy photosynthesis.

After the interaction of light with atmospheric particles such as aerosols and clouds, several types of change occur simultaneously in the incident photosynthetically active radiation (PAR) at the top of the canopy (TOC). When aerosols and clouds are induced in the atmosphere, the total PAR decreases and the fraction of diffuse PAR increases. The spectral composition of diffuse PAR also changes (Dye, 2004; Min, 2005). These changes can be partially or fully considered in existing atmospheric radiative transfer models for PAR estimation (Frouin et al., 1989; Eck & Dye, 1991; Gu et al., 2004; Kobayashi et al., 2004; Liang et al., 2006; Pinker & Laszlo, 1992; Van Laake & Sanchez-Azofeifa, 2004). However, due to their simplicity, these approaches do not take into account the angular variability of the incident diffuse PAR,

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while incident diffuse light has directionality due to the strong forward scattering properties in aerosols and clouds. Also few measurements are available for incident PAR, including its angular variability. Therefore, canopy photosynthesis calculations tend to use the isotropic diffuse PAR in their absorbed PAR (APAR) and canopy photosynthesis calculations (e.g., Alton et al., 2005; De Pury & Farquhar, 1997; Guillevic & Gastellu-Etchegorry, 1999; Sellers, 1985, 1987; Sellers et al., 1992). This assumption regarding the radiation regime gives rise to APAR and photosynthesis errors of up to 15% in some cases (Grant, 1985; Wang & Jarvis, 1990).

In addition to the radiation regime in the atmosphere, the 3-D structure of the canopy makes the spatial light environment (reflectance, transmittance, and absorption) heterogeneous, especially for the forest canopy. Crown structure, leaf area density in the crown, tree density, and leaf/background optical properties affect 3-D variations in the light environment. At the fine resolution scale, light interactions in lateral directions are not negligible, being typically less than the Landsat spatial scale (<30 m; Widlowski et al., 2006).

Further understanding of light interactions (reflectance, transmittance, and absorption) between the atmosphere and the 3-D canopy should be achieved by theoretical consideration using detailed radiative transfer calculations. Physically based coupled atmosphere–canopy radiative transfer simulation enables the user to evaluate canopy photosynthesis under various atmospheric scenarios.

Several models exist for the calculation of 3-D canopy radiative transfer (e.g., Gastellu-Etchegorry et al., 1996; Govaerts & Verstraete, 1998; Myneni et al., 1991; North, 1996). Although 3-D canopy radiative transfer models may be linked to atmospheric radiative transfer models by the off-line simulation, which describes the angular distribution of atmosphere or canopy radiation at the atmosphere–canopy boundary via parametric interfaces (e.g. Widlowski et al., 2001), the most convenient and promising approach to quantitatively investigate the relationship between atmospheric properties and the 3-D canopy light environment is to use a fully coupled atmosphere–canopy radiative transfer model, which enables accurate treatment of multiple scattering between the atmosphere and canopy.

The objective of this study is to describe a 3-D Monte Carlo radiative transfer model (Forest Light Environmental Simulator, FLiES) that can calculate various forest light environmental parameters (canopy reflectance, irradiance at TOC and forest floor, and APAR) including its spatial variation. While 3-D radiative transfer scheme in cloudy atmosphere is one of the potential approaches for the use of our objective, typical spatial scale is quite different between atmosphere (10–1000 km^2) and canopy (0.01–1.0 km^2) models and computation time is likely to become huge. Therefore we used 1-D radiative transfer scheme in cloudy atmosphere as an initial step.

We emphasize the coupled simulation in atmosphere–vegetation systems to investigate the relationship between the change in atmospheric radiation regime, and APAR and canopy photosynthesis variation in the vegetation canopy. This work is an extension of the calculation conducted by Kobayashi et al. (2007).

2. Model description

Several Monte Carlo canopy radiative transfer models, which are based on different numerical approaches, have been proposed for bidirectional reflectance factor (BRF) calculations. As an extension of the calculation of Kobayashi et al. (2007), we developed a model using the fundamental theory behind Monte Carlo modeling discussed in past studies (e.g., Antyufeev & Marshak, 1990; Iwabuchi, 2006; North, 1996; Ross & Marshak, 1988). We used Antyufeev and Marshak's (1990) method of Monte Carlo photon transport combined with North's (1996) geometric–optical hybrid forest canopy scene. To directly combine the 1-D plane parallel Monte Carlo atmospheric radiative transfer model with the canopy module, we employed the same numerical techniques and sampling methods in both the 1-D atmosphere and the 3-D canopy.

2.1. Simulation scene and optical properties of scattering media

Fig. 1 illustrates the simulation scene, which consists of a plane parallel atmosphere and 3-D vegetation canopy. Table 1 summarizes the atmospheric conditions used in this study. The atmosphere is divided into 12 plane parallel layers, including the height from 0 km (TOC) to 50 km. Each layer has a different density of molecules, aerosols, and cloud particles with different optical properties. We used LOWTRAN-7 (Kneizys et al., 1988) to pre-compute the molecular absorption coefficients under six typical atmospheric profiles, and we used ten aerosol and six cloud types modeled by Hess et al. (1998). Optical properties such as the extinction coefficient for unit volume (β), single scattering albedo (ω), and phase function (p) of each aerosol and cloud type was pre-computed. When we specify the atmospheric profile, aerosol type, and cloud type, the averaged β, ω, and P in the kth atmospheric layer were calculated by averaging the optical properties of all constituents.

$$\beta_{\mathrm{atm},k} = \beta_{\mathrm{m}} + \beta_{\mathrm{a}} + \beta_{\mathrm{c}} \tag{1}$$

$$\omega_{\mathrm{atm},k} = \frac{\omega_{\mathrm{m}}\beta_{\mathrm{m}} + \omega_{\mathrm{a}}\beta_{\mathrm{a}} + \omega_{\mathrm{c}}\beta_{\mathrm{c}}}{\beta_{\mathrm{m}} + \beta_{\mathrm{a}} + \beta_{\mathrm{c}}} \tag{2}$$

$$P_{\mathrm{atm},k} = \frac{\omega_{\mathrm{m}}\beta_{\mathrm{m}}p_{\mathrm{m}} + \omega_{\mathrm{a}}\beta_{\mathrm{a}}p_{\mathrm{a}} + \omega_{\mathrm{c}}\beta_{\mathrm{c}}p_{\mathrm{c}}}{\omega_{\mathrm{m}}\beta_{\mathrm{m}} + \omega_{\mathrm{a}}\beta_{\mathrm{a}} + \omega_{\mathrm{c}}\beta_{\mathrm{c}}}. \tag{3}$$

The subscripts atm, m, a, and c indicate the atmosphere, molecular, aerosol, and cloud, respectively.

In the canopy layer, we used a 3-D canopy object scene (Fig. 1). The tree canopy was modeled as a combination of geometric shapes representing the tree crowns (e.g., cones, cylinders and ellipsoids). The stem was modeled as a cylinder and did not enter the tree crown. Instead, the woody matter within the tree crown was modeled as a single object of identical shape, but half the dimensions, located at the lower part of the tree crown. Leaf area density (u) and branch area density (b) within the single canopy and branch media were assumed to be spatially uniform. Understory vegetation was modeled as a plane parallel layer. In the canopy layer, we assumed that photons interact only with