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A Comparison of Two Canopy Radiative Models in Land Surface Processes

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ABSTRACT

This paper compares the predictions by two radiative transfer models—the two-stream approximation model and the generalized layered model (developed by the authors) in land surface processes—for different canopies under direct or diffuse radiation conditions. The comparison indicates that there are significant differences between the two models, especially in the near infrared (NIR) band. Results of canopy reflectance from the two-stream model are larger than those from the generalized model. However, results of canopy absorptance from the two-stream model are larger in some cases and smaller in others compared to those from the generalized model, depending on the cases involved. In the visible (VIS) band, canopy reflectance is smaller and canopy absorptance larger from the two-stream model compared to the generalized model when the Leaf Area Index (LAI) is low and soil reflectance is high. In cases of canopies with vertical leaf angles, the differences of reflectance and absorptance in the VIS and NIR bands between the two models are especially large.

Two commonly occurring cases, with which the two-stream model cannot deal accurately, are also investigated. One is for a canopy with different adaxial and abaxial leaf optical properties; and the other is for incident sky diffuse radiation with a non-uniform distribution. Comparison of the generalized model within the same canopy for both uniform and non-uniform incident diffuse radiation inputs shows smaller differences in general. However, there is a measurable difference between these radiation inputs for a canopy with high leaf angle. This indicates that the application of the two-stream model to a canopy with different adaxial and abaxial leaf optical properties will introduce non-negligible errors.

Key words: generalized canopy radiative transfer model, two-stream approximation model, canopy reflectance, canopy absorptance

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1. Introduction

Global vegetation, with croplands, prairies, forests etc., occupies more than half of the total land surface area and determines the mass and energy transfer characteristics between the atmosphere and the underlying surface to a certain extent. In land surface processes, radiative transfer within the plant canopy directly affects energy, water vapor, and carbon cycles in climate models through earth surface albedo and canopy absorptance.

Earth surface albedo (or simply, albedo) is defined as the ratio of reflected incident solar radiation to incident solar radiation at the Earth's surface. It is a basic control factor for the surface energy budget (Dickinson, 1983). Charney (1975) proposed the famous biogeophysical feedback theory in the Sahel region that overgrazing and devegetation leads to less surface vegetation, which raises the ground's albedo and, in turn, due to a change in energy balance, the Earth's surface becomes a radiative heat source. Radiative cooling of the atmosphere over the Sahara due to the enhancement and sustenance of downwelling air leads to the expansion of the desert margin. Later, Charney et al. (1977) supported this earlier hypothesis through GISS GCM experiments. A series of studies with GCMs following this (Sud and Fennessy, 1982; Chervin, 1979; Carson and Sangster, 1981) further supported Char-

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ney's hypothesis. Statistical tests have shown that the atmosphere circumfluence and climate are sensitive to a change of surface albedo.

So the surface albedo, especially an accurate description of surface albedo with vegetation coverage, is very important in climate models. The increase in spatial resolutions from 100 km to 50 km (and even 10 km) in modern climate models also calls for a high-resolution albedo inventory or a spatially-explicit albedo specification (Hahmann and Dickinson, 2001). It has been suggested that an absolute accuracy of 0.02–0.05 is desirable for albedo in climate studies (Henderson-Sellers and Wilson, 1983; Sellers, 1993). With other conditions unchanged, the system energy input caused by a change in surface albedo of 0.01 is almost equivalent to that caused by a 1% change in the solar constant, which indicates the importance of surface albedo and its accurate estimation over different land surfaces (Li, 2000). Hence, research on a radiative transfer model in a vegetated canopy that provides accurate surface albedo for climate models is an important and urgent task in the development of land surface process models.

Canopy absorptance is also one of the major drivers of photosynthesis, dry-matter production, and energy exchange between the land surface and atmosphere (Wang, 2003). It depends upon the beam fraction of incident radiation, canopy structure, the optical properties of plant elements, and the underlying soil surface (Ross, 1981).

Various radiative transfer models in a vegetated canopy have been summarized by Myneni et al. (1989). The two-stream approximation scheme is one among them that is widely used in land surface process models (Sellers et al., 1986, 1996a,b; Dickinson et al., 1986). The two-stream scheme has been used to deal with radiative transfer of special substances for many years. The basic procedure in applying it to vegetation is to expand a complex function in the control equations into Legendre functions and then truncate them to the first order closure to get a simple solution. After reviewing several variants of the two-stream approximation model in the calculation of atmospheric radiation, Meador and Weaver (1980) presented a unified form of the variants and introduced a new and improved method. Dickinson (1983) introduced this new two-stream method to estimate radiative transfer in a vegetated canopy.

Goudriaan (1977) and Norman and Jarvis (1975) proposed layered radiative transfer models, which are an analogue of the physical process of radiative transfer in the canopy. Based on this kind of model, a more general layered radiative transfer scheme (called a generalized model) is proposed. The generalized model can deal with more general cases such as non-uniform incident diffuse radiation, differences in optical properties of different vegetation layers, and differences in adaxial and abaxial leaf optical properties (Dai and Sun, 2006). In this model, the angular distributions of diffuse radiation and leaf inclination angles are equally divided into nine inclination angles, and the complex mutual interactions of radiation from different inclination directions with leaves having different inclination angles are carefully considered. The total LAI of the canopy is divided into so many layers that the effects of mutual shading interaction and multiple scattering within the same layer can be neglected. Goudriaan (1977) suggested that the restriction $dL_j \leqslant 0.1$ for each sub-layer is applicable. The detailed derivation of this model can be found in the paper of Dai and Sun (2006).

An albedo precision within 0.02–0.05 can meet the requirements of climate model prediction. With a simple integrable solution, the two-stream transfer model has been accepted and used by many previous researchers, however few have paid attention to the precision of its application to vegetation, let alone the errors induced in the case where the two-stream model cannot resolve different adaxial and abaxial leaf optical properties. In this paper, a comparison and analysis of radiative transfer results from the two-steam model and the generalized model (Dai and Sun, 2006) will be conducted. A reflectance difference of 0.02 is taken as the standard for a non-negligible difference.

2. Description of the two models and the experimental designs

2.1 *Two-stream radiative transfer model*

We assume that diffuse radiative fluxes are isotropic in the upward and downward directions. Supposing that the leaf adaxial and abaxial optical properties are identical, the two-stream approximation model used to model radiative transfer in plant canopies is given in the following form (Dickinson, 1983; Sellers, 1985):

$$\begin{aligned} -\bar{\mu}(dI\uparrow/dL)+[1-(1-B)\tilde{\omega}]I\uparrow-\tilde{\omega}BI\downarrow \\ =\tilde{\omega}\bar{\mu}KB_0\exp(-KL)\,, \end{aligned} \tag{1a}$$

$$\begin{aligned} \bar{\mu}(dI\downarrow/dL)+[1-(1-B)\tilde{\omega}]I\downarrow-\tilde{\omega}BI\uparrow \\ =\tilde{\omega}\bar{\mu}K(1-B_0)\exp(-KL)\,, \end{aligned} \tag{1b}$$

where $I\uparrow$ and $I\downarrow$ are the upward and downward diffuse radiative fluxes normalized by the incident flux respectively, μ is the sine of the inclination of the incident beam, $K=G(\mu)/\mu$ is the optical depth of the direct beam per unit leaf area, $G(\mu)$ is the relative projected area of leaf elements in the direction μ, $\omega = \alpha + \tau$ is the scattering coefficient, α is the leaf reflectance, τ is the leaf transmittance, and L is the cumulative LAI. B and B_0 are upscattering parameters for the diffuse and direct beams respectively.

$$\omega B = \frac{1}{2}[\alpha + \tau + (\alpha - \tau)\cos^2\bar{\lambda}] ,$$

$\bar{\lambda}$ is the mean leaf inclination angle,

$$\cos^2\bar{\lambda} = \left(\frac{1+\chi_{\rm L}}{2}\right)^2 ,$$

and $\chi_{\rm L}$ is the departure index of leaf angle distribution to the spherical distribution.

$$B_0 = \frac{1+\bar{\mu}K}{\tilde{\omega}\bar{\mu}K} a_{\rm s}(\mu) ,$$

$\bar{\mu}$ is the average inverse diffuse optical depth per unit leaf area, and $\alpha_{\rm s}(\mu)$ is the single scattering albedo.

The first term on the left-hand side of Eq. (1a) refers to the attenuation of upward flux, the second term refers to the diffuse contribution from the same direction to the upward flux, the third term refers to the contribution from the opposite direction, and the last term on the right-hand side of Eq. (1a) refers to the contribution of the solar beam radiative flux to the upward flux. The terms in Eq. (1b) have similar meanings to those in Eq. (1a).

Equations (1a) and (1b) can be solved as an exact solution with appropriate boundary conditions as follows (Sellers, 1985):

For direct incident radiation, the appropriate top boundary condition is $I\downarrow = 0$ for $L = 0$, and the bottom boundary condition is $I\uparrow = \rho_s[I\downarrow + \exp(-KL_{\rm T})]$ for $L = L_{\rm T}$, where ρ_s is the soil reflectance and $L_{\rm T}$ is the total LAI. The corresponding solution of Eqs. (1a) and (1b) yields (Sellers, 1985):

$$I\uparrow = \frac{h_1\exp(-KL)}{\sigma} + h_2\exp(-hL) + h_3\exp(hL) ,$$

$$I\downarrow = \frac{h_4\exp(-KL)}{\sigma} + h_5\exp(-hL) + h_6\exp(hL) .$$

For diffuse radiation, the appropriate top boundary condition is $I\downarrow = 1$ for $L = 0$, and the bottom boundary condition is $I\uparrow = \rho_s I\downarrow$ for $L = L_{\rm T}$. Then, the corresponding solution is given as:

$$I\uparrow = h_7\exp(-hL) + h_8\exp(hL) ,$$

$$I\downarrow = h_9\exp(-hL) + h_{10}\exp(hL) ,$$

where coefficients such as σ and h_1 to h_{10} are given in Sellers (1985). Note that there is an error in the expression for h_4 in the appendix of Sellers (1985). The correct expression is $h_4 = -fp_3 - cd$ (Wang, 2003; Sellers et al., 1996a).

2.2 *Generalized layered radiative transfer model*

Let us denote the upward and downward scattered radiation fluxes at inclination angle β'_k between layer j and $j-1$ by $\phi_{\rm u}(\beta'_k, j)$ and $\phi_{\rm d}(\beta'_k, j)$, the adaxial leaf reflectance and transmittance as ρ_j and τ_j, and the abaxial leaf reflectance and transmittance as ρ'_j and τ'_j for layer j. Then, the equations for the downward and upward radiation leaving j at β'_k are given by Dai and Sun (2006):

$$\begin{aligned}\phi_{\rm d}(\beta'_k, j+1) = {} & \phi_{\rm d}(\beta'_k, j)\sum_{\lambda_n=1}^{N} g(\lambda_n, L_j)M_{\rm t}(\beta'_k, \lambda_n) + \\ & \sum_{\lambda_n=1}^{N} g(\lambda_n, L_j)B_{\rm l}(\beta'_k, \lambda_n)\sum_{\beta_k=1}^{K} M_{\rm i}(\beta_k, \lambda_n)\times \\ & [\phi_{\rm d}(\beta_k, j)(\rho_j\zeta_{\rm f} + \rho'_j\zeta_{\rm b} + \tau_j\xi_{\rm f} + \tau'_j\xi_{\rm b}) + \\ & \phi_{\rm u}(\beta_k, j+1)(\rho_j\xi_{\rm b} + \rho'_j\xi_{\rm f} + \tau_j\zeta_{\rm b} + \tau'_j\zeta_{\rm f})] + \\ & \sum_{\lambda_n=1}^{N} g(\lambda_n)B_{\rm l}(\beta'_k, \lambda_n)I_{\rm b}(z = L_j)dL_j\frac{G(\beta_0, \lambda_n)}{\sin\beta_0}\times \\ & (\rho_j\zeta_{\rm f,B} + \rho'_j\zeta_{\rm b,B} + \tau_j\xi_{\rm f,B} + \tau'_j\xi_{\rm b,B}) ,\end{aligned} \tag{2a}$$

$$\begin{aligned}\phi_{\rm u}(\beta'_k, j) = {} & \phi_{\rm u}(\beta'_k, j+1)\sum_{\lambda_n=1}^{N} g(\lambda_n, L_j)M_{\rm t}(\beta'_k, \lambda_n) + \\ & \sum_{\lambda_n=1}^{N} g(\lambda_n, L_j)B_{\rm l}(\beta'_k, \lambda_n)\sum_{\beta_k=1}^{K} M_{\rm i}(\beta_k, \lambda_n)\times \\ & [\phi_{\rm d}(\beta_k, j)(\rho_j\xi_{\rm f} + \rho'_j\xi_{\rm b} + \tau_j\zeta_{\rm f} + \tau'_j\zeta_{\rm b}) + \\ & \phi_{\rm u}(\beta_k, j+1)(\rho_j\zeta_{\rm b} + \rho'_j\zeta_{\rm f} + \tau_j\xi_{\rm b} + \tau'_j\xi_{\rm f})] + \\ & \sum_{\lambda_n=1}^{N} g(\lambda_n, L_j)B_{\rm l}(\beta'_k, \lambda_n)I_{\rm b}(z = L_j)dL_j\frac{G(\beta_0, \lambda_n)}{\sin\beta_0}\times \\ & (\rho_j\xi_{\rm f,B} + \rho'_j\xi_{\rm b,B} + \tau_j\zeta_{\rm f,B} + \tau'_j\zeta_{\rm b,B}) ,\end{aligned} \tag{2b}$$

where $\beta_k (k = 1, \ldots, 9)$ is the inclination of incident diffuse light, β_0 is the inclination angle of the Sun, β'_k is the inclination of scattered radiation, $g(\lambda_n,\ L_j)$ is the leaf angle distribution function for a leaf with an inclination angle of λ_n at layer j in the canopy, $G(\beta_0, \lambda_n)$ is the G function, which is the projection of leaves inclined at λ_n to the solar beam direction with inclination β_0, and $\overline{G(\beta_0)}$ is the average G function of leaves with angle distribution $g(\lambda_n, L_j)$ to the solar beam direction β_0. L_j is the cumulative LAI from the canopy top to layer j, $M_{\rm i}(\beta_k, \lambda_n)$ is the intercepted coefficient of layer j and

$$M_{\rm i}(\beta_k, \lambda_n) = dL_jG(\beta_k, \lambda_n)/\sin\beta_k ,$$

where dL_j is the LAI of layer j. $M_{\rm t}(\beta'_k, \lambda_n)$ is the penetration coefficient of layer j. $\xi_{\rm f}, \xi_{\rm b}, \zeta_{\rm f}$, and $\zeta_{\rm b}$ in Eqs. (2a) and (2b) are the adaxial and abaxial leaf reflectance and transmittance distribution functions for the upscattering of downward diffuse radiation. $\xi_{\rm f,B}, \xi_{\rm b,B}, \zeta_{\rm f,B}$, and $\zeta_{\rm b,B}$ are functions for the solar beam, which is indicated by the subscript B. All these functions depend upon the incident light inclination angle β_k (β_0 for solar beam), scattered light inclination angle β'_k, and the leaf inclination angle λ_n. For detailed derivations and expressions of the above parameters, please refer to Dai and Sun (2006). $B_{\rm l}(\beta'_k, \lambda_n)$ is the anisotropic scattering distribution function, defined as

$$B_{\rm l}(\beta'_k, \lambda_n) = \frac{B_{\rm u}(\beta'_k) M_{\rm i}(\beta'_k, \lambda_n)}{\sum\limits_{\beta_k=1}^{9} B_{\rm u}(\beta_k) M_{\rm i}(\beta_k, \lambda_n)} ,$$

where $B_{\rm u}(\beta'_k)$ is the distribution function for isotropic diffuse radiation (Goudriaan, 1977).

The top and bottom boundary conditions of the generalized model are similar to those of the two-stream model. If the incident radiation at the canopy top, the LAI, leaf angle distribution, and the corresponding leaf and soil optical parameters (leaf reflectance, leaf transmittance, and soil reflectance) for the specific wave band are given, the radiative transfer within the canopy can be determined easily by the model.

Compared with the two-stream scheme, the generalized model can be used in more general cases: in the anisotropic distribution of both incident sky radiation and diffuse radiation within the canopy, uneven optical properties of adaxial and abaxial leaf surfaces, and differing leaf angle distributions in each layer. It expands greatly upon the application of research on radiative transfer within the canopy (Dai and Sun, 2006).

2.3 *Simulation experiments*

In this paper, we compare the generalized model with the two-stream model in detail in order to find out the resolution and application range of the two-stream model and to provide the basic idea for designing reasonable radiative transfer schemes in land process models. As mentioned above, canopy reflectance and canopy absorptance are the two important components, so comparison of the models mainly deals with these. We handle diffuse radiation and direct beams with different incidences separately and consider various combinations of different angle distributions, optical properties (leaf reflectance and transmittance), and LAIs of leaves in the canopy. Three LAIs of one, five and eight are given to represent different typical vegetation types, two sets of leaf optical properties are given to cover the VIS and NIR wave bands, and two soil reflectance values are given, where the larger value represents snow cover over the ground surface. The leaves have different incident angles. This requires a considerably large amount of computation for the comparison. To describe the process easily, we classify the various experiments with the different combinations of LAI, leaf optical properties, and soil reflectance into two groups shown in the Appendix. Group N1 includes the n1−n6 sub-group covering the combination of leaf optical properties in the VIS band, soil reflectance (small or large), and LAI (low, medium or high). Group N2 includes the n7−n12 sub-group covering the combination of leaf optical properties in the NIR band, soil reflectance (low or large) and LAI (low, medium or high). There are two kinds of leaf angle distributions: lumped distribution mode and distributed distribution mode. In the lumped mode, the leaves are concentrated in a specific inclination angle, such as 40°, 45°, and so on. In the distributed mode, we consider the typical leaf angle distributions that exist in the real world, such as spherical, horizontal, vertical, planophile, erectophile, plagiophile, and extremophile (Ross, 1981; Goudriaan, 1988).

For the two-stream model used in SiB (A simple biosphere model), BATS (Biosphere Atmosphere Transfer Scheme) and other models, the leaf inclination angle is represented by the mean inclination angle $\bar{\lambda}$ and calculated through the so-called distribution index x_L describing the leaf inclination behavior (Goudriaan, 1977). The relation between $\bar{\lambda}$ and χ_L is

Table 1. Comparisons of canopy reflectance for the two models with various leaf angle distributions in case n1 (LAI=1, $\rho = 0.1, \tau = 0.1, \rho_s = 0.8$) in the VIS band under diffuse radiation.

Leaf angle distribution	Canopy reflectance Generalized model—two-stream model
40°	0.02
45°	0.03
50°	0.05
55°	0.05
60°	0.05
65°	0.05
70°	0.05
Horizontal	0
Planophile	0
Plagiophile	0.03
Erectophile	0.04
Spherical	0.04
Extremophile	0.03
Vertical	−0.04

Table 2. Comparisons of canopy absorptance of the two models with various leaf angle distributions in case n1 (LAI=1, $\rho = 0.1, \tau = 0.1, \rho_s = 0.8$) and n2 (LAI=1, $\rho = 0.1, \tau = 0.1, \rho_s = 0.2$) in the VIS band under diffuse radiation.

Leaf angle distribution	Canopy absorptance Generalized model—two-stream model			
	n1		n2	
	Difference	Relative difference	Difference	Relative difference
40°	0.021	3.0%	0.023	4.1%
45°	0.044	6.3%	0.049	8.9%
50°	0.055	8%	0.061	11.2%
55°	0.061	9.0%	0.067	12.6%
60°	0.062	9.3%	0.067	12.8%
65°	0.059	8.9%	0.063	12.2%
70°	0.055	8.4%	0.057	11.2%
Horizontal	0	0	0	0
Planophile	−0.013	2%	−0.015	3%
Plagiophile	0.04	6%	0.04	8%
Erectophile	0.052	7.8%	0.055	10.5%
Spherical	0.051	7.5%	0.055	10.2%
Extremophile	0.04	6%	0.05	8%
Vertical	−0.049	7.8%	−0.045	9.2%

$$\cos^2 \bar{\lambda} = \left(\frac{1+\chi_L}{2}\right)^2$$

(see the program code of SSiB). Since the range of χ_L applicable to most vegetation is $-0.4-0.6$ (Goudriaan, 1977), the corresponding scope for mean leaf angle $\bar{\lambda}$ is about $40° - 70°$. This is also the applicable range of the two-stream model in the SiB and BATS models. So, when the two models are compared, we capture the leaf inclination angles within this range.

The general layered model was taken as the base for comparisons. A canopy reflectance difference of 0.02 and a relative difference (with the generalized model as the base) in the canopy absorptance of 5% were taken as the non-negligible limits in the difference between the two models.

3. Comparison and analysis of the two radiative models

3.1 *Diffuse incident radiation*

With horizontal leaf angles and a planophile leaf angle distribution, all of the radiative transfer results (such as canopy reflectance, canopy transmittance, canopy absorptance, and soil absorptance) are exactly the same and almost the same, respectively, for the two models for all the combination cases in the Appendix, and the differences can be ignored as described previously (Dai and Sun, 2006).

The differences in canopy reflectance of the two models increase as the leaf angle increases, however the nature of the differences is not the same between the VIS and NIR bands.

In the VIS band, most of the differences in canopy reflectance for the two models are not obvious and can be ignored. However, differences of around 0.02–0.05 exist only in case n1, and the reflectances of the two-stream model are smaller (see Table 1). In Table 1, only when the leaf angle is vertical is the reflectance of the two-stream model larger.

The difference in canopy absorptance between the two models is large with low LAI (LAI=1); it increases as the soil reflectance decreases, and it increases first before decreasing slightly as the leaf angle increases (Table 2). With a low leaf angle, such as 40°, the difference is negligible. When the leaf angle is above 40°, the relative difference reaches 5%, which cannot be neglected. The difference reaches its maximum when the leaf angle is 60°. The difference and the relative difference are 0.062 and 9.3% respectively in case n1, and 0.067 and 12.8% respectively in case n2 (Table 2). The differences are between 0.04 and 0.07, and the relative differences are between 6% and 12.8%. The values of canopy absorptance from the two-stream model are smaller in most cases, but larger when the leaf angle is vertical.

In the NIR band, the canopy reflectance values of the two-stream model are smaller than those of the generalized model in most cases, but they agree well in cases of low LAI (e.g., LAI=1). The difference in canopy reflectance between the two models increases as the LAI increases. With the same LAI, it increases as soil reflectance decreases. It changes greatly with soil reflectance in the case of low LAI, but little in the case of high LAI. Under the condition of low LAI and high soil reflectance (e.g., LAI=1 and ρ_s=0.8), the

Table 3. Comparisons of canopy reflectance between the two models with various leaf angle distributions in all cases but case n7 in the NIR band under diffuse radiation.

Leaf angle	Canopy reflectance Generalized model—two-stream model
40°	0.02
45°	0.02
50°	0.02−0.03
55°	0.03−0.04
60°	0.03−0.05
65°	0.03−0.05
70°	0.03−0.06
Horizontal	0
Planophile	0
Plagiophile	0.02
Erectophile	0.02−0.04
Spherical	0.02−0.03
Extremophile	0.02
Vertical	−0.06–0.08

difference in canopy reflectance for the two models reaches its minimum. In fact, the difference in case n7 is small enough to be neglected. Table 3 shows quite obvious differences in canopy reflectance between the two models with various leaf angle distributions in all cases but case n7 in the NIR band under diffuse radiation.

Vertical leaf angle distribution is a particularly special case, because the differences in canopy reflectance between the two models are generally very large (excluding case n8), around 0.06−0.08, and the results of the two-stream model are larger.

The differences in canopy absorptance between the two models in the NIR band are not very obvious. With very low leaf angle (e.g., a leaf angle of 40°) and a plagiophile distribution, the differences can be neglected. Large differences appear mostly under the condition of comparatively low leaf angle and low LAI, and canopy absorptance of the two-stream model is larger. Also, the differences take place mostly under the condition of high LAI (e.g., case n11) and comparatively high leaf angles, but canopy absorptance of the two-stream model is smaller. When the leaf angle is vertical, the relative differences of canopy absorptance all become larger than 10%, and canopy absorptance of the two-stream model is smaller.

Figure 1 shows large differences in upward and downward radiative fluxes in the canopy between the two models with a 70° leaf angle (only cases n11 and n12 are given).

Table 4 shows a comparison of canopy absorptance between the two models with a 50° leaf angle and very low LAI (LAI=1). We can see that the canopy absorptance of the two-stream model is larger, and the relative differences are 8% and 11.2% in cases n1 and n2 respectively (in the VIS band), while the differences are comparatively smaller for cases n7 and n8 (in the NIR band).

The differences in the results for the two models with a spherical leaf angle distribution are also comparatively large, and the difference trends are also in agreement with those at a 55° or 65° leaf angle. However, the maximum difference in canopy reflectance between the two models with a spherical leaf angle distribution is 0.03. The differences in canopy absorptance in the NIR band can be neglected. The spherical distribution is a uniform distribution, which is generally the case in an actual plant stand, especially in herb and grass vegetation (Ross, 1981). In fact, the effect of the spherical distribution is approximately equivalent to that of a 57.3° mean leaf angle when the leaf angle index is χ_L=1. According to the approximate formula

$$\cos^2 \bar{\lambda} = \left(\frac{1+\chi_L}{2}\right)^2 ,$$

we can derive that $\bar{\lambda} = 60°$. Table 5 shows a comparison of the results between spherical leaf angle distribution and a 60° mean leaf angle for the generalized model. We can see that both the canopy reflectance and canopy absorptance results agree with each other very well.

3.2 *Direct incident radiation*

Since the results under direct radiation are more complex, we consider the solar beams incident from nine different inclination angles and also the various combinations of leaf optical properties, soil reflectance, and canopy structures. Because the amount of data is very large, we compare a selection of representative solar beam incident angles, such as 5°, 25°, 45°, 65°, and 85° for analysis.

When the leaf angle is horizontal, no matter which direction the solar beam is incident from, the radiative transfer results are the same, and they are also theoretically the same as the results for the same conditions under diffuse radiation. The results of the generalized model fit this deduction, but the results of the two-stream model under beam radiation do not agree with those under diffuse radiation. However, the results of the two-stream model agree well with those of the generalized model under diffuse radiation, so we can say that the results of the two-stream model under beam radiation are inaccurate under this condition. The differences in canopy reflectance for the two models in the VIS band are around 0.01, which can be neglected, and are all above 0.02 in the NIR

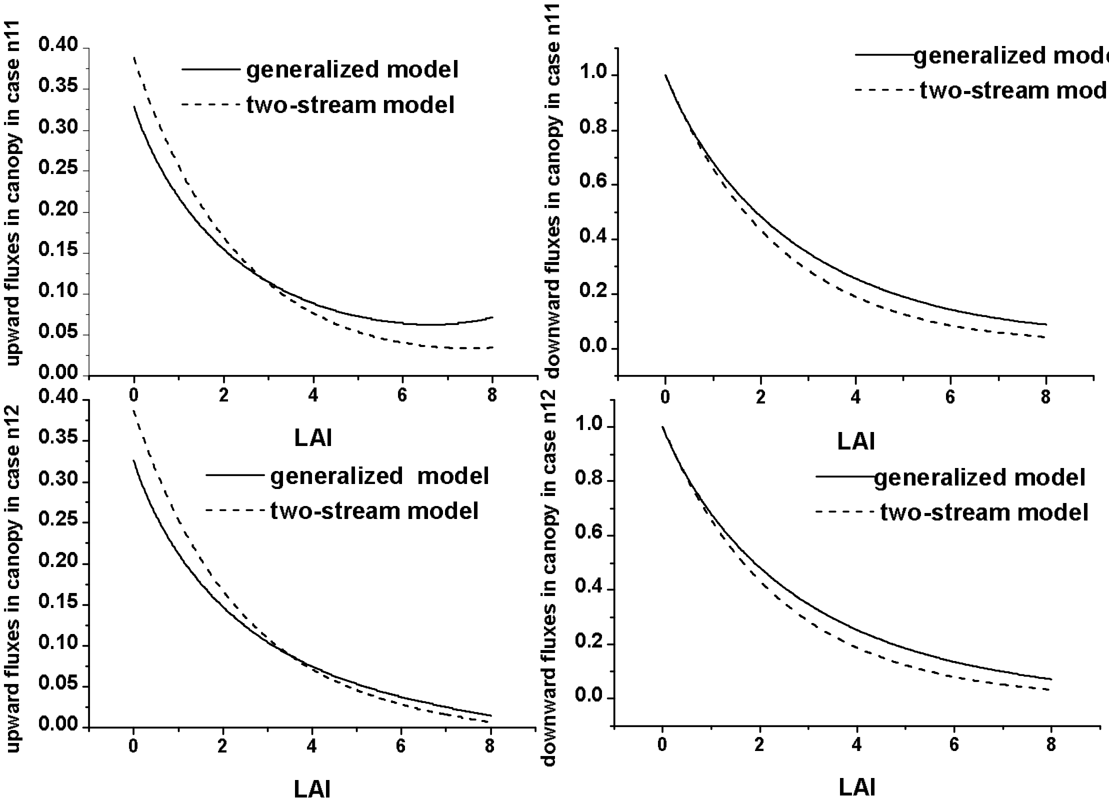

Fig. 1. Comparisons of upward and downward radiation fluxes in the canopy between the generalized model and the two-stream model ($\bar{\lambda}$=70°, n11: LAI=8, ρ_t=0.5, τ_l=0.3, ρ_s=0.8; n12: LAI=8, ρ_l=0.5, τ_l=0.3, ρ_s=0.2).

Table 4. Comparison of canopy absorptance between the two models under diffuse radiation ($\bar{\lambda}$ = 50°, LAI=1). Details regarding the cases can be found in the Appendix.

Case	Generalized model	Two-stream model	Generalized model−two-stream model	Relative difference
n1	0.687	0.742	−0.055	8%
n2	0.543	0.604	−0.061	11.2%
n7	0.195	0.207	−0.012	6.2%
n8	0.620	0.596	0.024	3.9%

band, most of which reach 0.04. In the NIR band, the results of the two-stream model are smaller. The differences in canopy reflectance strongly depend upon soil reflectance with low LAI (e.g., LAI=1), and they increase as soil reflectance decreases. The differences in canopy reflectance between the two models are comparatively small and can be neglected in the VIS band with the planophile distribution.

For other leaf angles or leaf angle distributions in the VIS band, there are considerable differences in canopy reflectance between the two models in case n1 when the solar inclinations are high ($\beta_0 \geqslant 45°$) (see Table 6). Generally, canopy reflectance of the two-stream model is smaller, however the opposite is true for the reflectances with a vertical leaf angle. As the leaf angle increases, differences in canopy reflectance between the two models become larger. They are only a little different when the Sun angle is 45°.

In addition, the canopy reflectance of the two-stream model is 0.02 smaller than that of the generalized model in case n1 with a 55° leaf angle for a solar inclination angle of 25°. The canopy reflectance of the two-stream model is also 0.02 smaller in cases n3−n5 with a plagiophile leaf angle distribution for a solar inclination angle of 5°.

The canopy reflectances of the two-stream model are larger than those of the generalized model with a vertical leaf angle distribution. The differences be-

Table 5. Comparison of canopy reflectance, canopy transmittance, canopy absorptance, and soil absorptance results between the conditions of a 60° leaf angle and a spherical leaf angle distribution for the generalized model under diffuse radiation (generalized model results for 60° leaf angle minus that for spherical leaf angle distribution). Details of the six cases can be found in the Appendix.

Case	Canopy reflectance	Canopy transmittance	Canopy absorptance	Soil absorptance
n7	0	0.007	−0.001	0.001
n8	−0.008	0.012	−0.001	0.009
n9	−0.011	0.016	0.007	0.003
n10	−0.013	0.014	0.002	0.011
n11	−0.013	0.009	0.011	0.002
n12	−0.014	0.008	0.007	0.007

Table 6. Comparison of canopy reflectance between the two models in case n1 (LAI=1, $\rho = 0.1, \tau = 0.1, \rho_s = 0.8$) with various leaf angle distributions in the VIS band under beam radiation.

Leaf angle distribution	Canopy reflectance Generalized model result−two-stream model result		
	45° solar angle	65° solar angle	85° solar angle
40°	0.019	0.016	0.015
45°	0.034	0.028	0.026
50°	0.04	0.035	0.031
55°	0.042	0.04	0.034
60°	0.039	0.044	0.037
65°	0.034	0.048	0.039
70°	0.027	0.048	0.043
Horizontal	0	0	0
Planophile	0	0	0
Plagiophile	0.031	0.03	0.029
Erectophile	0.025	0.034	0.038
Spherical	0.025	0.03	0.032
Extremophile	0.021	0.031	0.034
Vertical	−0.041	−0.033	−0.033

tween the two models are generally very large at low solar incidence and reach their maximum of 0.05−0.06 at a solar inclination angle of 25°. For very high solar incidence angles (viz., 65° and 85°), sometimes the differences are instead low, and can be neglected.

The differences in canopy absorptance between the two models in the VIS band with a horizontal leaf angle and with the planophile distribution are almost all small enough to be neglected. Non-negligible differences exist with other leaf angle distributions, including plagiphile, extremophile, erectophile, and spherical. Generally, under the condition of both low LAI (e.g., cases n1 and n2) and comparatively high solar beam incidence ($\beta_0 \geqslant 45°$), the relative differences are around 5%–7%, and even above 10% in some cases. The canopy absorptance of the two-stream model is generally larger, except for the cases with low leaf angles (e.g., 40° or 45°) and with the plagiophile leaf angle distribution. For a vertical leaf angle, the differences in canopy absorptance between the two models are generally very large with low LAI. The relative differences are around 6%–9%. With high LAI, the differences are also large at other solar beam incidence angles, such as 25°, and the relative differences are 6%. With a vertical leaf angle, the canopy absorptance values of the two-stream model are all smaller.

In the NIR band, when only the incident solar beam is considered, the differences in canopy reflectance between the two models are around 0.02 (e.g., case n7), or larger with both horizontal leaf angles (mentioned before) and the planophile leaf angle distribution, with the differences reaching 0.04 in most cases. The canopy reflectance of the two-stream model is smaller.

For other leaf angles or leaf angle distributions in the NIR band, the differences in canopy reflectance between the two models are generally very, large; only in some cases with both low leaf angle (e.g., cases n8, n10, n11, and n12) and 45° solar beam incidence are the differences small enough to be neglected. Also, with a high leaf angle (e.g., 65° or 70°), the differences are comparatively small. Basically, the differences first decrease then increase with the increase of the solar beam incidence. They increase with the decrease in

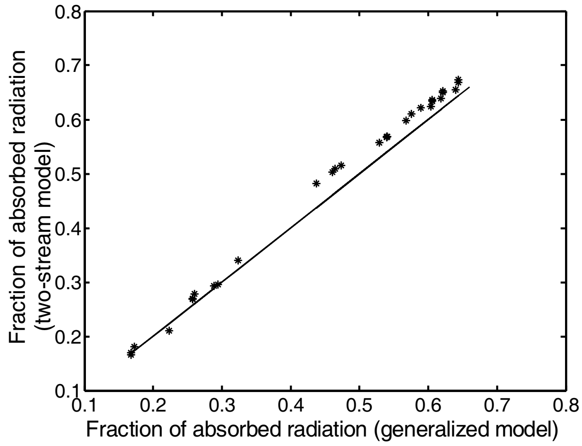

Fig. 2. Comparison of canopy absorptance between the two models in the NIR band when only solar beam incidence is considered ($\bar{\lambda} = 50°$; details regarding the combinations in the NIR band can be found in the Appendix).

soil reflectance, and the trend is obvious for low LAI. Generally, the differences in canopy reflectance are comparatively small in case n7, being around 0.02, or even small enough to be neglected. The canopy reflectance of the two-stream model is generally smaller, yet, it is still a special case with a vertical leaf angle in that the differences are generally large and the results of the two-stream model are larger. The differences are sometimes larger too when the leaf angle is high (e.g., 65° and 70°).

With only the incident solar beam considered, the differences in canopy absorptance between the two models in the NIR band are comparatively large with a horizontal leaf angle or the planophile leaf angle distribution, and with high LAI. The relative differences are 7%–16% and 5%–12% with horizontal leaf angle and the planophile leaf angle distribution respectively. The results of the two-stream model are larger. In addition, under the conditions of very low LAI and low soil reflectance (e.g., case n8) with the planophile leaf angle distribution, the results of the two-stream model are generally smaller, however the relative differences surpass 5% for the sunbeam incidence at 5°. Generally, the results of the two-stream model are larger; they are only smaller in some cases with a vertical leaf angle, and some other leaf angles in case n8.

In the NIR band, the differences of canopy absorptance for the two models are large with the extremophile leaf angle distribution and comparatively high LAI. With low LAI, the differences are comparatively large only when the Sun incidence is 65° or 85°. The maximum of the relative differences is 8%, and the results of the two-stream model are larger.

The canopy absorptance results of the two-stream model are generally much smaller than those of the generalized model with a vertical leaf angle in the NIR band. Most of the relative differences are in the range of 10%–20%.

In the NIR band, the differences of canopy absorptance are generally large when the Sun incidence is comparatively low (e.g., 5° and 25°) with a 40° or 45° leaf angle. The maximum differences are 19% and 13% respectively, and the results of the two-stream model are larger. The relative differences for the two models are around 5% under other Sun incidences in case n10 with a 45° leaf angle.

When the Sun incidence is very low (e.g., 5°), or comparatively high (e.g., 65° or 85°), the differences in canopy absorptance between the two models are large with a spherical leaf angle distribution in the NIR band. The maximum relative difference is 6%, and the results of the two-stream model are larger.

The differences of canopy absorptance are generally (around 2/3) larger than 5% for the two models in the NIR band with a 50° leaf angle, and the maximum difference is 10%. The results of the two-stream model are larger. Figure 2 provides a comparison of canopy absorptance between the two models, and we can see that the differences are very large. The large differences appear under the conditions of high LAI and low Sun incidence. The maximum differences in cases n9, n10, n11 and n12 are 0.042, 0.045, 0.042 and 0.044 respectively.

With 55°, 60°, 65°, and 70° leaf angles, and plagiophile and erectophile leaf angle distributions, the differences in canopy absorptance are large with comparatively low Sun incidence, and the relative differences are 8%, 8%, 10%, 12%, 14%, and 8% respectively. The differences are also larger, mostly in case n8, and when the sun incidence is very high, with a 55° leaf angle. The results of the two-stream model are larger in all cases but case n8.

3.3 *Further discussion on the deficiency of the two-stream model*

The radiative transfer results computed by the two-stream model with a horizontal leaf angle under solar beam radiation are not equal to those under diffuse radiation, which is obviously not in accordance with theoretical expectations. Namely, according to the linear superposition theory, the diffuse radiative transfer should be the sum of all direct radiations from every angle. Not only the results with a horizontal leaf angle abide by this law, but those with other angles, in principle, do also. Table 7 shows a comparison of canopy reflectance, canopy transmittance, canopy absorptance, and soil absorptance with the erectophile leaf angle distribution between the two models under

Table 7. Comparison of canopy reflectance (refl), canopy transmittance (trans), canopy absorptance (vegabs) and soil absorptance (soilabs) between the two models under various solar beams and the erectophile distribution (LAI=5, ρ_l=0.5, τ_l=0.3, ρ_s=0.8). The diffuse results between the two models are also shown.

UOC	$\beta_0(^\circ)$	Generalized model				Two-stream model			
		refl	trans	vegabs	soilabs	refl	Trans	vegabs	soilabs
0.030	5	0.526	0.065	0.461	0.013	0.502	0.067	0.484	0.013
0.087	15	0.452	0.085	0.531	0.017	0.439	0.091	0.543	0.018
0.133	25	0.407	0.109	0.571	0.022	0.393	0.121	0.583	0.024
0.163	35	0.375	0.142	0.596	0.028	0.358	0.163	0.609	0.033
0.174	45	0.352	0.184	0.612	0.037	0.332	0.211	0.626	0.042
0.163	55	0.334	0.23	0.62	0.046	0.312	0.258	0.636	0.052
0.133	65	0.322	0.274	0.623	0.055	0.298	0.297	0.642	0.059
0.087	75	0.314	0.306	0.624	0.061	0.29	0.325	0.645	0.065
0.03	85	0.31	0.325	0.625	0.065	0.285	0.34	0.647	0.068
Sum of the solar beams result		0.365	0.189	0.597	0.038	0.346	0.209	0.612	0.042
Diffuse result		0.364	0.188	0.599	0.038	0.396	0.134	0.577	0.027
Direct−diffuse		0.001	0.001	−0.002	0	−0.050	0.075	0.035	0.015

Table 8. Comparison of results between different and the same adaxial and abaxial leaf optical properties under diffuse radiation (where the results with different adaxial and abaxial leaf optical properties are the base). For cases of different adaxial and abaxial leaf optical properties, $\rho = 0.5, \rho' = 0.3$; and for cases of the same adaxial and abaxial leaf optical properties, $\rho = \rho' = 0.5$; for other parameters, please refer to the Appendix.

Group	Difference in canopy reflectance		Difference in canopy absorptance	
	Horizontal leaves	Spherical leaves	Horizontal leaves	Spherical leaves
n7	0.055	0.068	−0.073	−0.083
n8	0.011	0.025	−0.036	−0.054
n9	0.032	0.058	−0.041	−0.069
n10	0.029	0.051	−0.049	−0.078
n11	0.029	0.054	−0.032	−0.058
n12	0.029	0.053	−0.036	−0.065

both a variety of solar beams and a uniform overcast sky distribution (UOC). The sum of all the direct canopy reflectance results by the generalized model is 0.365, and the diffuse canopy reflectance is 0.364; we can see that they agree well with each other. However, under the same conditions, the two results of the two-stream model are 0.346 and 0.396 respectively, and the difference is as large as 0.050.

4. Analysis of the limitations of the two-stream model

The two-stream model cannot distinguish between different adaxial and abaxial optical properties. Under the conditions of different leaf adaxial and abaxial optical properties, it takes the mean optical properties of both surfaces, or instead only takes the abaxial properties in the model. In addition, the two-stream model cannot distinguish between non-uniform diffuse radiation that is incident and that which is in the canopy. It takes diffuse radiation as uniform, because the basis for the derivation of the two-stream method is the assumption of uniform diffuse radiation. Therefore, some errors will be produced by using the two-stream model in these situations. In order to explore the possible errors and application scope of the two-stream model in these situations, several sensitivity studies using the generalized model were conducted. We compared results of the generalized model under conditions of different and the same adaxial and abaxial leaf optical properties, as well as results under conditions of uniform and non-uniform incident diffuse radiation.

4.1 *Comparison of results between different and the same adaxial and abaxial leaf optical properties*

The abaxial leaf reflectance is set to 0.3 for various combinations of the LAI, soil reflectance, and adaxial leaf reflectance and transmittance, which can be found in the Appendix. We suppose that the abaxial leaf transmittance is the same as the adaxial one, because in the real canopy, generally, the leaf adaxial

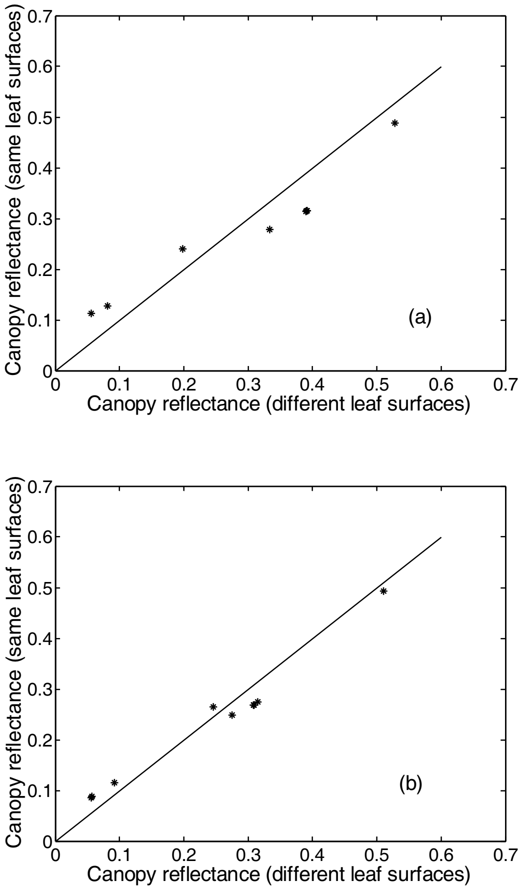

Fig. 3. (a) Comparison of canopy reflectances between cases of different and the same abaxial and adaxial leaf optical properties by the generalized model with a horizontal leaf angle under diffuse radiation. (Details regarding the various combinations of the LAI, leaf reflectance, leaf transmittance, and soil reflectance can be found in the Appendix). (b) As Fig. 3a, except for a spherical leaf angle distribution.

and abaxial transmittances differ only a little from each other. That is, in group N1, the adaxial and abaxial leaf reflectances are $\rho = 0.1$ and $\rho' = 0.3$, and in group N2, $\rho = 0.5$ and $\rho' = 0.3$, respectively. We take the above design as the conditions of different adaxial and abaxial leaf optical properties for our comparisons. For these conditions, in the two-stream model the value of leaf reflectance can be set to that of the adaxial surface. That is, $\rho = \rho' = 0.1$ in group N1 and $\rho = \rho' = 0.5$ in group N2 for the combinations in the Appendix. We take this to be the case for the same leaf adaxial and abaxial optical properties in the generalized model for comparison. We compare the radiative transfer results under the two conditions by the generalized model with horizontal and spherical leaves under diffuse radiation, and we find that in the NIR band, the differences between them are large. As shown in Table 8, the maximum difference in the canopy reflectance is 0.055 with horizontal leaves, and 0.068 with a spherical leaf angle distribution.

Under conditions of different adaxial and abaxial leaf optical properties for the comparisons mentioned above, in the two-stream model, the value of leaf reflectance may be set to the mean value of the adaxial and abaxial surfaces. That is, $\rho = \rho' = 0.2$ in group N1 and $\rho = \rho' = 0.4$ in group N2 for the combinations in the Appendix. We also take this as the case for the same leaf adaxial and abaxial optical properties in the generalized model for comparison. In comparing the canopy reflectance results for the two conditions, we find that the differences between them are large. Figure 3 shows the large differences in canopy reflectance between the two conditions by the generalized model; Fig. 3a is for horizontal leaves and Fig. 3b for a spherical leaf angle distribution. We can see that in most of the cases the differences are very large, and the maximum differences for horizontal leaves and a spherical leaf angle distribution are 0.076 and 0.04, respectively.

Figures 4a, b, and c show a comparison of canopy reflectance between different and the same adaxial and abaxial leaf optical properties with a spherical leaf angle distribution when the Sun incidence is 25°, 45° and 65° respectively. We can see that the differences are large for both of "*" and "○" cases, and the maximum differences are 0.074, 0.067 and 0.063, respectively. That's to say, both of the methods dealing with different abaxial and adaxial surfaces mentioned above in the model introduce large errors.

Therefore, there will be very large errors in the two-stream model because it cannot distinguish between the adaxial and abaxial leaf optical properties.

4.2 *Analysis under different sky diffuse radiation distributions*

For the uniform overcast sky distribution (UOC), the distribution of the nine incident angles of radiation is: $B_{\rm u}(\beta_k)$=0.030, 0.087, 0.133, 0.163, 0.174, 0.163, 0.133, 0.087, and 0.030, $k = 1, \ldots, 9$, which can be dealt with by both models. The two-stream model, however, cannot deal with non-uniform incident radiation, or that in the forest. The standard overcast sky (SOC) is a familiar non-uniform diffuse radiation distribution, and the distribution of its nine incident angles is: $B_{\rm s}(\beta_k)$=0.015, 0.057, 0.106, 0.150, 0.180, 0.184, 0.160, 0.110, and 0.038, $k = 1, \ldots, 9$, (Goudriaan, 1977). The simulated results under the two sky distributions by the generalized model are compared.

The canopy reflectances for the two sky distributions with horizontal leaves are the same. Also, with the spherical, erectophile and other leaf angle distribu-

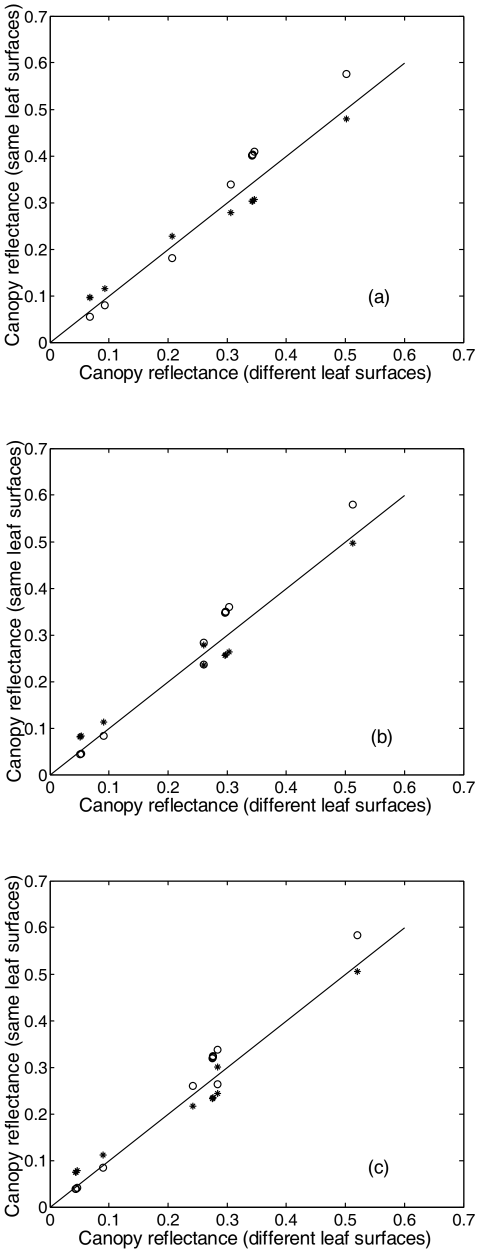

Fig. 4. (a) Comparison of canopy reflectance between cases of different and the same adaxial and abaxial leaf optical properties by the generalized model with a horizontal leaf angle at a solar beam incidence of 25°. (Details regarding the various combinations of the LAI, leaf reflectance, leaf transmittance, and soil reflectance can be found in the Appendix). For the different abaxial and adaxial leaf surfaces, $\rho' = 0.3$; $\circ$ for the same abaxial and adaxial leaf surfaces, $\rho = \rho' = 0.1$ in the VIS band and $\rho = \rho' = 0.5$ in the NIR band; $*$ for the same abaxial and adaxial leaf surfaces, $\rho = \rho' = 0.2$ in the VIS band and $\rho = \rho' = 0.4$ in the NIR band. (b) As Fig. 4a, except for a solar inclination angle of 45°. (c) As Fig. 4a, except for a solar inclination angle of 65°.

tions, the differences in canopy reflectance for the two sky distributions are not very large. They are around 0.01 in the N2 group and can be neglected. When the leaf angle is very high (much higher than 60°), the difference is around 0.02.

In fact, there are still other forms of non-uniform sky diffuse radiation. The two-stream model under non-uniform sky diffuse radiation will cause certain errors in some conditions.

5. Conclusions

There are differences between the generalized model and the two-stream model. Generally, with only incident diffuse radiation considered, the results of the two models are almost the same with low leaf angles. Their differences increase as the leaf angle increases. In the VIS band, the differences in canopy reflectance of the two models are larger than 0.02 only with low LAI and large soil reflectance (case n1). The differences in canopy absorptance are large with very low LAI (case n1 and case n2), and the relative differences are above 5%. Generally, in the VIS band, canopy reflectance is smaller and canopy absorptance larger for the two-stream model. In the NIR band, most of the comparison results indicate that canopy reflectances from the two models are large (excluding case n7) and indicate that canopy reflectances of the two-stream model are larger. The differences in canopy absorptance are large under some conditions, and the results of the two-stream model are sometimes smaller and sometimes larger.

When only an incident solar beam is considered, in the VIS band, the differences in canopy reflectance of the two models are generally large in case n1 when the solar beam incidence is larger than 45°, and the results of the two-stream model are smaller. The differences in canopy absorptance are generally large with low LAI (in cases n1 and n2) when the solar beam incidence is larger than 45°, and the results of the two-stream model are larger. In the NIR band, the differences in canopy reflectance of the two models are generally large, and the results of the two-stream model are smaller. The differences in canopy absorptance of the two models are large under some conditions, and the results of the two-stream model are sometimes smaller and sometimes larger.

The differences in radiative transfer results between the two models with a vertical leaf angle are all generally large.

The two-stream model cannot distinguish between the different adaxial and abaxial leaf optical properties, and it takes the adaxial value or the mean of the adaxial and abaxial values when it is applied. Comparisons of canopy reflectance of the different adaxial and abaxial leaf optical properties with that of the same adaxial and abaxial leaf optical properties by the generalized model show large differences (above 0.02) between them. So, the two-stream model will bring large errors under the conditions of different adaxial and abaxial leaf optical properties in the NIR band.

The two-stream model treats non-uniform incident diffuse radiation, or that in the canopy, as uniform. Comparing canopy reflectances of non-uniform incident diffuse radiation with those of uniform incident diffuse radiation by the generalized model indicates that the differences between them are around 0.02 with a high leaf angle. So, the two-stream model may cause large errors under conditions of non-uniform incident diffuse radiation with a high leaf angle.

In summary, the two-stream model oversimplifies the radiation and cannot simulate accurately the complex interactions between the light and the leaves. Further work is needed to simplify the generalized model and apply it in a land surface model.

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APPENDIX

Design of Experiment

The experiments n1−n12 indicate the status regarding various combinations of LAI, leaf reflection (ρ) and transmission (τ), and soil reflection (ρ_s).

Group N1 (VIS band):

n1: LAI=1, ρ=0.1, τ=0.1, ρ_s=0.8;
n2: LAI=1, ρ=0.1, τ=0.1, ρ_s=0.2;
n3: LAI=5, ρ=0.1, τ=0.1, ρ_s=0.8;
n4: LAI=5, ρ=0.1, τ=0.1, ρ_s=0.2;
n5: LAI=8, ρ=0.1, τ=0.1, ρ_s=0.8;
n6: LAI=8, ρ=0.1, τ=0.1, ρ_s=0.2;

Group N2 (NIR band):

n7: LAI=1, ρ=0.5, τ=0.3, ρ_s=0.8;
n8: LAI=1, ρ=0.5, τ=0.3, ρ_s=0.2;
n9: LAI=5, ρ=0.5, τ=0.3, ρ_s=0.8;
n10: LAI=5, ρ=0.5, τ=0.3, ρ_s=0.2;
n11: LAI=8, ρ=0.5, τ=0.3, ρ_s=0.8;
n12: LAI=8, ρ=0.5, τ=0.3, ρ_s=0.2.

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