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Four-stream Radiative Transfer Parameterization Scheme in a Land Surface Process Model*

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ABSTRACT

Accurate estimates of albedos are required in climate modeling. Accurate and simple schemes for radiative transfer within canopy are required for these estimates, but severe limitations exist. This paper developed a four-stream solar radiative transfer model and coupled it with a land surface process model. The radiative model uses a four-stream approximation method as in the atmosphere to obtain analytic solutions of the basic equation of canopy radiative transfer. As an analytical model, the four-stream radiative transfer model can be easily applied efficiently to improve the parameterization of land surface radiation in climate models.

Our four-stream solar radiative transfer model is based on a two-stream short wave radiative transfer model. It can simulate short wave solar radiative transfer within canopy according to the relevant theory in the atmosphere. Each parameter of the basic radiative transfer equation of canopy has special geometry and optical characters of leaves or canopy. The upward or downward radiative fluxes are related to the diffuse phase function, the *G*-function, leaf reflectivity and transmission, leaf area index, and the solar angle of the incident beam.

The four-stream simulation is compared with that of the two-stream model. The four-stream model is proved successful through its consistent modeling of canopy albedo at any solar incident angle.

In order to compare and find differences between the results predicted by the four- and two-stream models, a number of numerical experiments are performed through examining the effects of different leaf area indices, leaf angle distributions, optical properties of leaves, and ground surface conditions on the canopy albedo. Parallel experiments show that the canopy albedos predicted by the two models differ significantly when the leaf angle distribution is spherical and vertical. The results also show that the difference is particularly great for different incident solar beams.

One additional experiment is carried out to evaluate the simulations of the BATS land surface model coupled with the two- and four-stream radiative transfer models. Station observations in 1998 are used for comparison. The results indicate that the simulation of BATS coupled with the four-stream model is the best because the surface absorbed solar radiation from the four-stream model is the closest to the observation.

Key words: radiative transfer equation, four-stream approximation, four-stream radiative transfer model

1. Introduction

Researchers are currently trying to perfect land surface models. Many offline experimental results indicate that modeling results for sensible heat, latent heat and solar radiation absorbed by land surface are poor, especially for the last variable (Henderson-Sellers et al., 1993, 1995). Land albedo directly affects solar radiation absorbed by the surface, and canopy albedo is an important part of land albedo. With the demand for more detailed and accurate research on land surface processes, accuracy in canopy radiative models is required.

Canopy radiative process modeling uses the atmospheric radiative parameterization methods, with specially modified structural and optical characteristics. In the atmospheric sciences, four-stream discrete ordinate, spherical harmonic expansion, isosector approximation, and four-approximation models have been considered for atmospheric radiative flux

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computations (Liou, 2004). Liang and Townshend (1996) adopted a four-stream radiative transfer model based on atmospheric four-stream discrete ordinates. Tian et al. (2007) developed a four-stream isosector approximation for canopy radiative transfer based on the Li and Dobbie (1998) four-stream isosector approximation method. Compared to other models, four-stream radiative models are more accurate. Dai (2004) and Dai and Sun (2006) developed a complete model to deal with radiative transfer within a canopy based on the layered model of Norman and Ross.

The two-stream model developed by Dickinson (1983) is computationally efficient and can provide accurate analytical solutions. Sellers (1985) calculated the canopy hemisphere albedo in the visible (VIS) and near infrared (NIR) bands using the two-stream model, and provided analytical solutions.

In the 1990s, land surface process and canopy radiative models became more elaborate and detailed due to the advances of computers (Myneni et al., 1988, 1989; Ross, 1975, 1981). But many land surface models still use the two-stream radiative model, which is not very accurate. Therefore, it is necessary to develop more accurate four-stream radiative models.

In order to provide more accurate solutions to canopy albedo, we developed a four-stream radiative transfer model within canopy, using the four-stream approximation. This can reduce the bias in the land surface radiative transfer calculation. Our method can make the description of canopy radiative transfer more accurate while maintaining the computational efficiency of the two-stream approach.

Fu and Liou's (1992, 1993) radiative parameterization scheme, improved by Gu and Liou (2000, 2001), has obvious advantages. We adopted the same Fu-Liou's four-stream approximation method to develop our canopy radiative transfer scheme. The four-stream model will be coupled to the land surface and atmospheric models of the China National Climate Center to realize a unified atmosphere-vegetation radiative transfer scheme. Some climate system models used different radiative transfer parameterization schemes in the atmospheric model component and the land surface model component. This may induce negative influences on computational precision.

This paper is devoted to constructing a four-stream radiative transfer model to obtain more precise canopy albedo. The calculation bias of the surface radiative process will certainly have a conspicuous effect on land surface energy budget and other factors, such as land surface temperature and photosynthesis, and the effect above will inevitably feeds back to the atmospheric processes, which will then act on the whole atmospheric motion and earth-atmosphere system, and the accuracy of climate simulations will be affected thereby.

The within canopy four-stream model is based on the atmospheric radiative transfer theory. Each parameter of the basic canopy equation has a specific geometry and optical characteristic of leaves or canopy (Huang, 1997; Xu, 2005). We adopted the analytical formula of the Henyey-Greenstein phase function. The formula shows that the distribution of diffuse energy within the canopy is related to leaf transmission, leaf reflectivity, average leaf angle and the incident direct beam radiation direction. Parameterized formulas of other parameters are also proposed in this paper. Upward or downward radiative fluxes are related to the diffuse phase function, the G-function, leaf reflectivity, leaf transmission, leaf area index, and the solar angle of the incident beam.

The four-stream model solves a basic radiative transfer equation of the canopy. The basic radiative transfer equation is really a calculus equation. We gained an analytic solution for upward and downward radiative fluxes in the canopy by introducing the atmospheric four-stream approximation (Liou, 2004), and finally calculated and obtained canopy albedo.

The simulation is verified by comparing the two- and four-stream models simulated canopy albedos under the condition of horizontal leaf. The four-stream model is proven successful through its consistent modeling of canopy albedo at any solar incidence angle.

Because we have limited empirical canopy radiation data, a simulation test was carried out for the models. The valuable contribution of this paper is that we tested simulations of the four- and two-stream models using field observations. The paper carried out one experiment to evaluate simulations of a land surface model coupled with the two radiative transfer models.

2. Model development

Solar radiative transfer within canopy consists of three processes: extinction, single scattering, and multiple scattering (Huang, 1997). With these processes, one widely used canopy radiative transfer equation is:

$$-\mu\frac{\mathrm{d}I(\tau,\mu)}{\mathrm{d}\tau}+G(\mu)I(\tau,\mu)=\frac{\omega}{4\pi}\int\limits_{4\pi}P(\mu',\mu)G(\mu')\cdot I(\tau,\mu')\mathrm{d}\mu'+\frac{\omega}{4\pi}P(\mu_0,\mu)G(\mu_0)\pi I_0\exp\left[\frac{-G(\mu_0)\cdot\tau}{\mu_0}\right].\quad(1)$$

The equation is applied to full-grown vegetation. In Eq. (1), I is the diffuse intensity; $\mu=\cos\theta$, θ is the local zenith angle; $\mu_0=\cos\theta_0$, θ_0 is the solar zenith angle; πI_0 is the incident solar flux at the top of the canopy, and $G(\mu)$ or $G(\mu')$ are the geometry factors defined as the relative projected area of leaf elements in the direction $\cos^{-1}(\mu)$ or $\cos^{-1}(\mu')$, respectively. The terms $P(\mu',\mu)$ and $p(\mu_0,\mu)$ are normalized azimuthally independent phase functions. The term τ represents the cumulative leaf area index. Because the vertical coordinate is directed downward, a canopy is confined between depth zero (L=0) at the top and L=total leaf area at the bottom. Hence, τ is a measure of the depth of the canopy. In Eq. (1), the first term describes the divergence (net rate of photons streaming out of the canopy along the depth of the canopy) of the diffuse intensity in the direction μ. The second term describes the reduction of the diffuse intensity due to outward scattering and absorption by leaves. The third term describes the contribution to the diffuse intensity by multiple inward scattering, arising from the scattering of a radiation ray with solid angle $\mathrm{d}\mu'$ in the direction of μ' (Liou, 2004). The last term represents the generation of diffuse intensity in the direction μ due to single scattering of the direct solar radiation from $-\mu_0$ (the minus sign denotes that the direct solar radiation is always downward, penetrating to the specified depth L in the canopy).

These expressions use K for the optical depth of the direct beam per unit leaf area:

$$K=\frac{G(\mu)}{\mu}.\quad(2)$$

The G-function in Eq. (1) is defined as:

$$G(\Omega)=\frac{1}{2\pi}\int_0^{2\pi}\mathrm{d}\varphi_L\int_0^{\frac{\pi}{2}}g(\Omega_L)\mid\Omega_L\cdot\Omega\mid\sin\theta_L\mathrm{d}\theta_L.\quad(3)$$

Less regular leaf-angle distributions may be described by means of the X_L function of Ross (1975), whereby the departure of leaf angles from a spherical distribution is characterized by a simple expression:

$$X_L=\pm\int_0^{2/\pi}\mid 1-O(\theta)\mid\sin\theta\mathrm{d}\theta,\quad(4)$$

where θ is the leaf inclination angle relative to the horizontal plane and $O(\theta)$ is the leaf-angle distribution function. $X_L=0$ is for spherically arranged leaves, $+1$ for horizontal leaves and -1 for vertical leaves.

Goudriaan (1977) fitted a curve to datasets generated from Eq. (3), which provides reasonable estimates of the average leaf projection in any direction given a value of X_L:

$$G(\mu)=\phi_1+\phi_2\mu,\quad(5)$$

where $\phi_1=0.5-0.633X_L-0.33X_L^2$ and $\phi_2=0.877(1-2\phi_1)$.

The relationship between X_L and the average leaf angle $\overline{\lambda}$ is

$$\cos^2(\overline{\lambda})=(\frac{1+X_L}{2})^2.\quad(6)$$

In this new four-stream model, the canopy phase function adopts the Henyey-Greenstein phase function,

$$p(\mathit{\Theta})=(1-g^2)/(1+g^2-2g\cos\mathit{\Theta})^{\frac{3}{2}}.\quad(7)$$

As inferred from the analysis in the appendix of Norman and Jarvis (1975),

$$g=\frac{1}{2\omega}[\rho+t+(\rho-t)\cos^2\overline{\lambda}],\quad(8)$$

where ρ is the reflectivity, t the transmissivity of a leaf, ω the leaf scattering albedo, and $\overline{\lambda}$ the average leaf angle.

2.1 Radiation field decomposition

Following the four-stream approximation method (Liou, 2004) in the atmosphere, the basic equation of canopy can be discretized:

$$\mu_i\frac{\mathrm{d}I(\tau;\mu_i)}{\mathrm{d}\tau}=G(\mu_i)I(\tau,\mu_i)-\frac{\omega}{2}\sum_{l=0}^{N}\overline{\omega}_lP_l(\mu_i)\times\sum_{j=-n}^{n}a_jP_l(\mu_j)G(\mu_j)I(\tau;\mu_j)-\frac{\omega}{4\pi}\sum_{l=0}^{N}\overline{\omega}_lP_l(\mu_i)G(\mu_0)P_l(\mu_0)\pi I_0\mathrm{e}-G(\mu_0)\frac{\tau}{\mu_0}. \tag{9}$$

Consider two radiative streams in the upper and lower parts of the canopy, expanding the scattering phase function into four terms in line with the four radiative streams. To simplify Eq. (1), we define

$$b_{i,j}=\begin{cases} c_{i,j}/\mu_i & i=j,\\ (c_{i,j}-G(\mu))/\mu_i & i\neq j,\end{cases} \tag{10}$$

$$c_{i,j}=\frac{\omega}{2}a_j\sum_{l=0}^{N}\overline{\omega}_lp_l(\mu_i)p_l(\mu_j)G(\mu_j). \tag{11}$$

Further, we define the direct solar beam in the form

$$I_\Theta=\mathrm{e}^{-G(\mu_0)\frac{\tau}{\mu_0}}\times\frac{\pi I_0}{2\pi}. \tag{12}$$

Using the preceding definitions, Eq. (1) becomes

$$\frac{\mathrm{d}I_i}{\mathrm{d}\tau}=-\sum_{j=-n}^{n}b_{i,j}I_j-b_{j,0}I_\Theta\ \ i=-2,2,j=-2,2. \tag{13}$$

We note that the simple Eq. (13) is the same as the simplified atmosphere basic equation. Coefficients $b_{i,j}$, $b_{i,0}$, and I_Θ are defined differently. Equation (13) expanded is really in a matrix form, consisting of four first-order differential equations. We can solve the matrix to get the upward and downward radiative intensities at each depth.

2.2 Four-stream approximation

Similar to atmospheric radiation parameterization, the four-stream model within the canopy considers two radiative streams at the upper and lower canopy surfaces. The Gauss quadratures and weights in the four-stream model are μ_1=0.3399810, μ_2=0.8611363, and a_1=0.6521452, a_2=0.3478548 when the leaf arrangement is anisotropic. When isotropic surface reflection is included in this approximation, double Gauss quadratures and weights are μ_1=0.2113248, μ_2=0.7886752, and a_1=0.6521452, a_2=0.3478548.

Each parameter can be defined according to the canopy geometry and optical characteristics. At the same time, the canopy basic equation can be solved by referring to the atmospheric four-stream approximation. Equation (13) is expanded into a four-by-four matrix, which represents the contribution of multiple scattering. Thus, the derivative of diffuse intensity at a specific quadrature angle is the weighted sum of the multiple scattered intensities from all four quadrature angles. The last term represents the contribution of the unscattered component of direct solar flux at position L.

The solution is as follows:

$$\begin{bmatrix} I_2\\ I_1\\ I_{-1}\\ I_{-2}\end{bmatrix}=\begin{bmatrix}\phi_2^+\mathrm{e}_2 & \phi_1^+\mathrm{e}_1 & \phi_1^-\mathrm{e}_3 & \phi_2^-\mathrm{e}_4\\ \Theta_2^+\mathrm{e}_2 & \Theta_1^+\mathrm{e}_1 & \Theta_1^-\mathrm{e}_3 & \Theta_2^-\mathrm{e}_4\\ \Theta_2^-\mathrm{e}_2 & \Theta_1^-\mathrm{e}_1 & \Theta_1^+\mathrm{e}_3 & \Theta_2^+\mathrm{e}_4\\ \phi_2^-\mathrm{e}_2 & \phi_1^-\mathrm{e}_1 & \phi_1^+\mathrm{e}_3 & \phi_2^+\mathrm{e}_4\end{bmatrix}\times\begin{bmatrix} G_2\\ G_1\\ G_{-1}\\ G_{-2}\end{bmatrix}+\begin{bmatrix} Z_2^+\\ Z_1^+\\ Z_{-1}^-\\ Z_{-2}^-\end{bmatrix}\mathrm{e}^{-G(\mu_0)\tau/\mu_0}. \tag{14}$$

The parameters of Eq. (14) can be computed successively as shown in Liou (1988, 2004), except for coefficients $G_i(\pm1, 2)$.

2.3 Boundary condition

Coefficients $G_i(\pm1,2)$ in Eq. (14) are determined from the radiation boundary conditions.

There are two ways for radiation to transfer into the canopy: incident direct beam radiation and incident diffuse radiation. We handle diffuse radiation and direct beam radiation separately with different incidences and consider various combinations of different angle distributions.

Considering the total leaf area index L_T and incident solar beam radiation transfer, the boundary condition of Eq. (14) is:

$$I_{-1}\downarrow(0,-\mu_1)=0 \quad (\tau_0=0,\ \ \mu_1 \text{ direction}), \quad (15a)$$

$$I_{-2}\downarrow(0,-\mu_2)=0 \quad (\tau_0=0,\ \ \mu_2 \text{ direction}). \quad (15b)$$

This indicates no diffuse radiation from the top of the canopy.

We now include surface reflection in the scattered intensity and flux density equations. The ground is considered to reflect according to Lambert's law, with a reflectivity (or surface albedo) of p_s. Under this condition, the diffuse upward intensity is constant. The boundary condition of $\tau_1 = L_T$ is:

$$I_1\uparrow(\tau_1,\mu_1)=I_2\uparrow(\tau_1,\mu_2) =\frac{p_s[2\pi a_1\mu_1 I_{-1}\downarrow(\tau_1,-\mu_1)+2\pi a_2\mu_2 I_{-2}\downarrow(\tau_1,-\mu_2)+\pi I_0\exp(-KL_T)]}{2\pi(a_1\mu_1+a_2\mu_2)}. \quad (15c)$$

Equation (15c) indicates that the diffuse radiation from the bottom of this layer includes leaf element diffusion, scattered beam radiation, and unscattered transmission beam radiation.

$$I_{-1}\downarrow(0,-\mu_1)=1 \quad (\tau_0=0,\ \ \mu_1 \text{ direction}), \quad (16a)$$

$$I_{-2}\downarrow(0,-\mu_2)=1 \quad (\tau_0=0,\ \ \mu_2 \text{ direction}). \quad (16b)$$

Equations (16a) and (16b) indicate that all incident radiation is diffuse and incident beam radiation is zero at the top of the canopy.

The ground albedo is also considered to reflect according to Lambert's law, with a reflectivity (or surface albedo) of p_s; the upward radiation in $\tau_1 = L_T$ is written as:

$$I_1\uparrow(\tau_1,\mu_1)=I_2\uparrow(\tau_1,\mu_2) =\frac{p_s[2\pi a_1\mu_1 I_{-1}\downarrow(\tau_1,-\mu_1)+2\pi a_2\mu_2 I_{-2}\downarrow(\tau_1,-\mu_2)]}{2\pi(a_1\mu_1+a_2\mu_2)}. \quad (16c)$$

Equation (16c) presents the upward radiative of canopy bottom is diffuse radiative reflected by land surface.

After coefficient $G_i(\pm 1, 2)$ is defined by introducing the boundary condition, the upward and downward radiation fluxes in the depth of canopy can be calculated.

3. Cross-validation of models

In this paper, we compare the four-stream model with the two-stream model in detail in order to determine the resolution and application range of the four-stream model. The four-stream model can determine the whole canopy albedo and radiative flux at a depth L in the canopy. We will cross-check the four-stream model results with the two-stream model simulations.

Goudriaan (1977) conducted a crop micrometeorology simulation study with some observation data, and conduded that the canopy albedo under the condition of horizontal leaf is the same, no matter which direction the solar beam is incident from. Results are the same for incident diffuse radiation. Our new four-stream model, if it is a good model, should produce the same results (a) for different solar radiation parameters under the horizontal leaf condition and (b) with the two-stream model results since the latter are verified and widely used.

We use a two-stream radiative transfer model as a comparison model to evaluate the four-stream model. The four-stream model simulation is tested by comparing the canopy albedo under the horizontal leaf condition generated through within canopy simulations of the two-stream radiative model.

In order to access the performance of the four-stream model, we used eighteen cases with different leaf area indices, scattering coefficients, and soil reflectivities. The parameters in each case are presented in Table 1. Cases n1−n6 represent typical vegetation in the VIS band, cases n6−n12 represent typical vegetation in the NIR band, and the leaf single scattering albedo for n12−n18 are optical properties of leaves in the real world.

Figure 1 shows simulations from the four- and two-stream models of the canopy albedo under incident diffuse radiation. The results of the two models

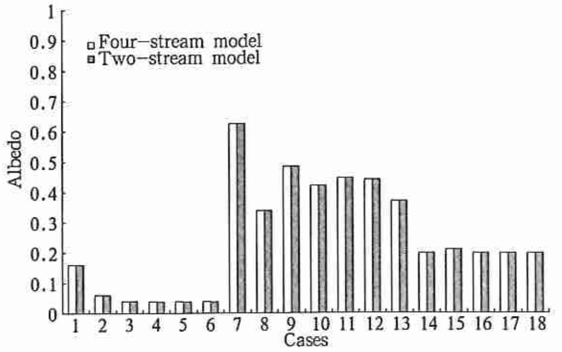

Fig.1. Canopy albedo simulated by the four- and two-stream models using incident diffuse radiative transfer and a horizontal leaf distribution.

Table 1. A list of experiments (n1−n18) for various combinations of leaf area index, leaf reflection, transmission, and soil reflection

Case	LAI	ω	ρ_s	Case	LAI	ω	ρ_s
1	1	0.14	0.8	10	3	0.85	0.2
2	1	0.14	0.2	11	6	0.85	0.8
3	3	0.14	0.8	12	6	0.85	0.2
4	3	0.14	0.2	13	1	0.55	0.8
5	6	0.14	0.8	14	1	0.55	0.2
6	6	0.14	0.2	15	3	0.55	0.8
7	1	0.85	0.8	16	3	0.55	0.2
8	1	0.85	0.2	17	6	0.55	0.8
9	3	0.85	0.8	18	6	0.55	0.2

are very close, almost identical. This proves that the four-stream model is successful.

For incident radiation with any solar incident angle, the results are the same for any direction of beam incidence (figures omitted). The model is again proved successful through its production of identical canopy albedo estimates for any solar incidence angle.

4. Model comparisons and test experiments

Although in a canopy radiation field, canopy albedo and absorptance are important parameters, we only consider simulations of canopy albedo. This is because our aim is to couple the four-stream model to a climate model, which only relates to canopy albedo. Thus this paper only compares the canopy albedo simulations of the two- and four-stream models under radiative incident beam and diffuse incidence when the leaf angle distribution is spherical and vertical. In the end, we verify the simulations of the two models using field observations.

4.1 Simulation comparisons

We have already proven that the new four-stream radiative transfer model is successful since it obtained the same modeling results for the canopy albedo with those from the two-stream model under a horizontal leaf angle distribution. When the average leaf angle is above zero, the results simulated by the two models become different. Here, we compare the two models for spherical and vertical leaf angle distributions with incident diffuse radiation and incident beam radiation, respectively.

4.1.1 Diffuse incident radiation

For incident diffuse radiation, we choose a leaf scattering albedo of 0.14 or 0.85. A value of 0.14 represents the leaf optical character in the VIS band and 0.85 the NIR band. When the leaf angle distribution is spherical, $X_L = 0$ and $G(\mu) = 0.5$. When the leaf angle distribution is vertical, $X_L = -1$ and $G(\mu) = \frac{2}{\pi}(1 - \mu^2)^{1/2}$. Because of limited space, we only show a figure of leaf area index from 1 to 6 with a soil reflectivity of 0.2.

Figures 2a and 2b show that the simulation differs for the two models with spherical leaf angle distribution. When the scattering albedo of the leaf elements is small in the VIS band, there are slight differences that are almost less than 0.01 and are negligible; when the scattering albedo of the leaf elements is large in the NIR band, the simulations have obvious differences. The results of the two-stream model are larger than those of the four-stream model. The absolute difference maximum is up to 0.05. Figures 2c and 2d show the simulations of the two models with vertical leaf distribution. For the vertical distribution, the simulation difference of the two models is larger than that for a spherical distribution. When the scattering albedo of the leaves is small in the VIS band, the difference is obviously above 0.01. The results from the two-stream model are larger than those from the four-stream model. When the scattering albedo of the leaves is large in the NIR band, the simulated canopy albedo becomes large with an increase in the leaf area

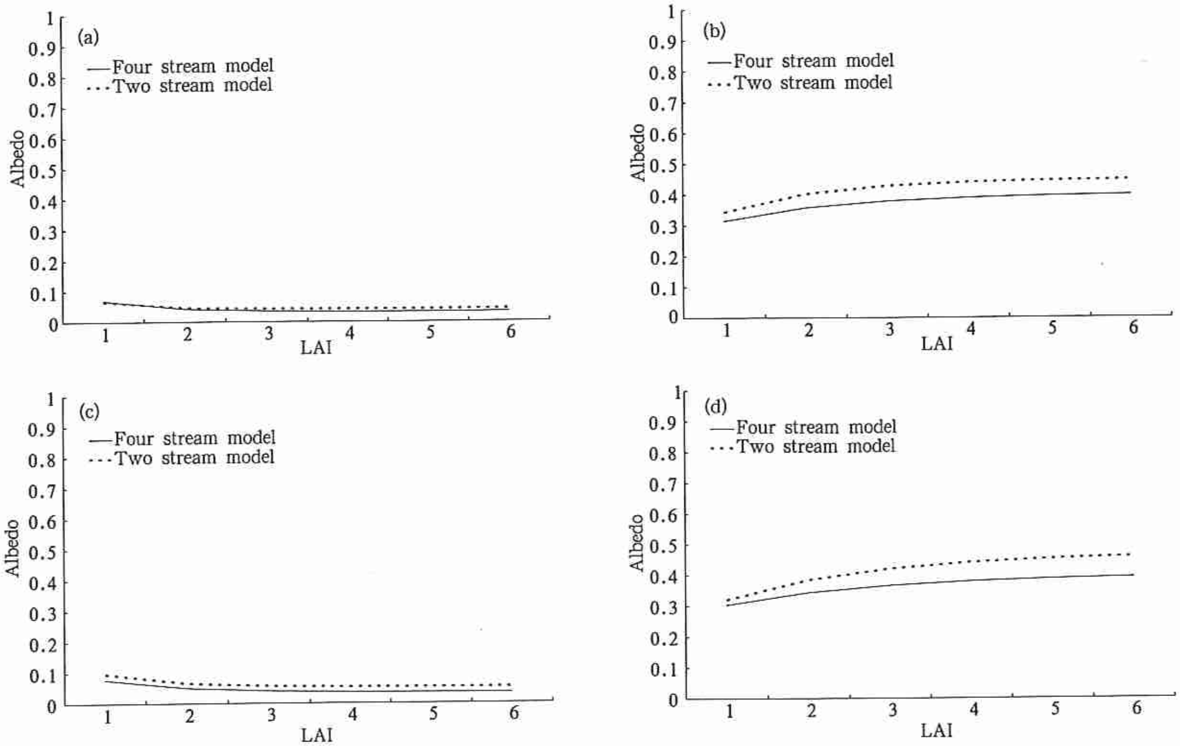

Fig.2. Comparison of canopy albedos from the two- and four-stream models under diffuse incident radiative transfer with (a)ω=0.14, ρ_s=0.2; (b)ω=0.85, ρ_s=0.2; (c)ω=0.14, ρ_s=0.2; (d)ω=0.85, ρ_s=0.2. Note that (a) and (b) are for spherical distribution; (c) and (d) are for vertical distribution.

index. The simulations of the two-stream model are higher than those of the four-stream model in all cases.

The nature of the differences is the same for the VIS and NIR bands with spherical and vertical leaf angle distributions (Fig. 2). The canopy albedo simulated by the two models decreases with an increase in leaf area index when the leaf angle has a spherical distribution. In contrast, the canopy albedo simulated by the two models increases with leaf area index when the leaf angle has a vertical distribution. Thus, the simulated canopy albedo differs for a specific leaf angle index under different leaf angle distributions.

4.1.2 Direct beam radiation

Since the results under direct beam radiation are complex, we consider solar beams incident from nine different inclination angles (5°, 15°, 25°, 35°, 45°, 55°, 65°, 75°, and 85°). For incident beam radiation, we choose a leaf scattering albedo of 0.14 or 0.85, representing the VIS or NIR bands. We show the results for a leaf area index of 1 or 6 and soil reflectivity of 0.2. Figures 3a and 3b show simulations with a leaf scattering albedo of 0.14 in the VIS band, a spherical leaf angle, and leaf area index of 1 and 6, respectively. When the leaf area index is 1 or 6, the results for the two models almost agree; errors can be ignored. When single leaf scattering is 0.85 in the NIR band with a leaf area index of 1 (Fig. 3c), the results of the two-stream model are lower than those of the four-stream model by 0.01 and errors cannot be ignored when the sun angle is above 35° (maximum is 0.021). However, the difference is barely noticeable when the solar angle is lower than 35° and the leaf area index is 6 (Fig. 3d).

Figures 3e and 3f show the simulations with a leaf scattering albedo of 0.14 in the VIS band, a vertical leaf angle distribution, and a leaf area index of 1 or 6, respectively.

When the leaf area index is 1 (Fig. 3e), the difference in the VIS band with a solar angle above 35° is obvious, and the results from the two-stream model are larger than those from the four-stream model. The absolute difference with the sun angle above 35° is larger than 0.01, with a maximum of 0.031. However,

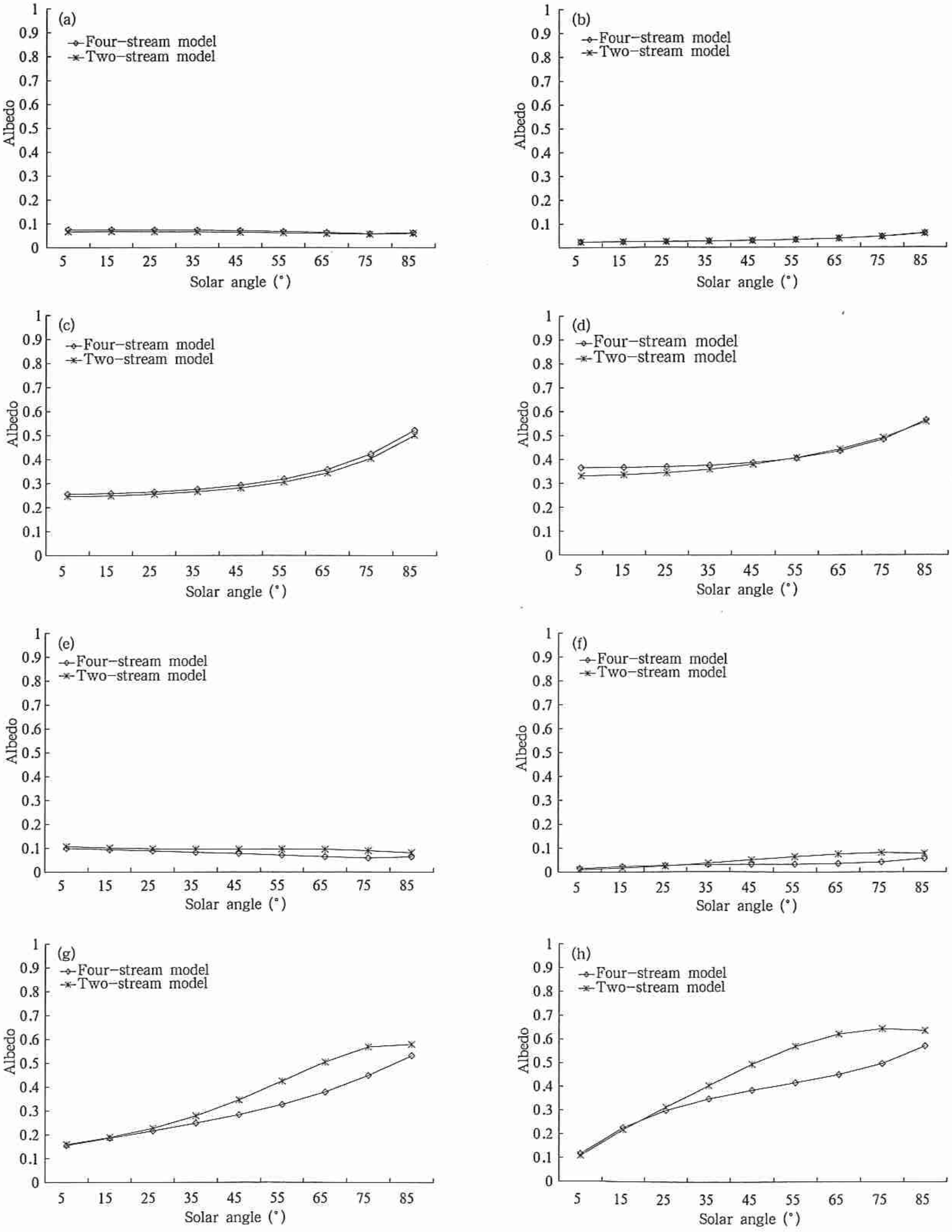

Fig.3. Comparison of canopy albedos from the two- and four-stream models under beam incident radiative transfer with (a)$\omega=0.14$, $\rho_s=0.4$, LAI=1; (b) $\omega=0.14$, $\rho_s=0.4$, LAI=6; (c) $\omega=0.85$, $\rho_s=0.4$, LAI=1; (d)$\omega=0.85$, $\rho_s=0.4$, LAI=6; (e)$\omega=0.14$, $\rho_s=0.4$, LAI=1; (f)$\omega=0.14$, $\rho_s=0.4$, LAI=6; (g)$\omega=0.85$, $\rho_s=0.4$, LAI=1; and (h) $\omega=0.85$, $\rho_s=0.4$, LAI=6; Note that (a) and (b) are for spherical distribution; (c)−(i) are for vertical distribution.

the results of the two-stream model are larger than those of the four-stream model by 0.01 when the solar angle is larger than 45° with a leaf area index of 6 (Fig. 3f). The maximum absolute difference is 0.04.

Figures 3g and 3h show the simulations for a leaf scattering albedo of 0.85 in the NIR band, a vertical leaf angle distribution, and a leaf area index of 1 or 6. When the leaf area index is 1, the difference is very obvious for a solar angle above 25°. The results of the two-stream model are obviously larger than those of the four-stream model. The absolute difference is larger than 0.03 for a sun angle above 35°. The maximum absolute difference is 0.12.

The results of the two-stream model are larger than those of the four-stream model by 0.01 when the solar angle is above 25° and the leaf area index is 6. The absolute difference is larger than 0.05 for a solar angle above 35°. The maximum is 0.17.

There are obvious differences between the two- and four-stream models when the leaf angle distribution is either spherical or vertical. In particular, the difference is salient when the leaf angle is vertical and the solar angle is above 25° or 35°. Because the four-stream model considers incident radiative transfer in two directions, but the two-stream model considers only one direction, and also because the *G*-function and distinction coefficients are different with different direction radiation incidence and leaf angles, there are indeed expectable differences in the simulations of the two models. This paper shows the results for a few special leaf angle distributions in order to clarify the differences of the two models. The differences exist for other leaf angle distributions as well (figures omitted).

4.2 Test experiments

In order to illuminate the advantage of the four-stream model, the four- and two-stream models are both coupled into the improved BATS (Biosphere Atmosphere Transfer Scheme) land surface model. The effect of the two models on the performance of BATS simulations is evaluated.

The simulations of BATS using the two- and four-stream models are compared with station observations at Shouxian, Anhui in China from July 10 to August 4 in 1998.

The results in Fig. 4 indicate that the simulation of BATS coupled with the four-stream model is the best among the three simulations using different radiative transfer models, because the surface absorbed solar radiation calculated from the four-stream model is the closest to the observation. Previously, by use of station data during 1998 GAME/HUBEX IOP, we

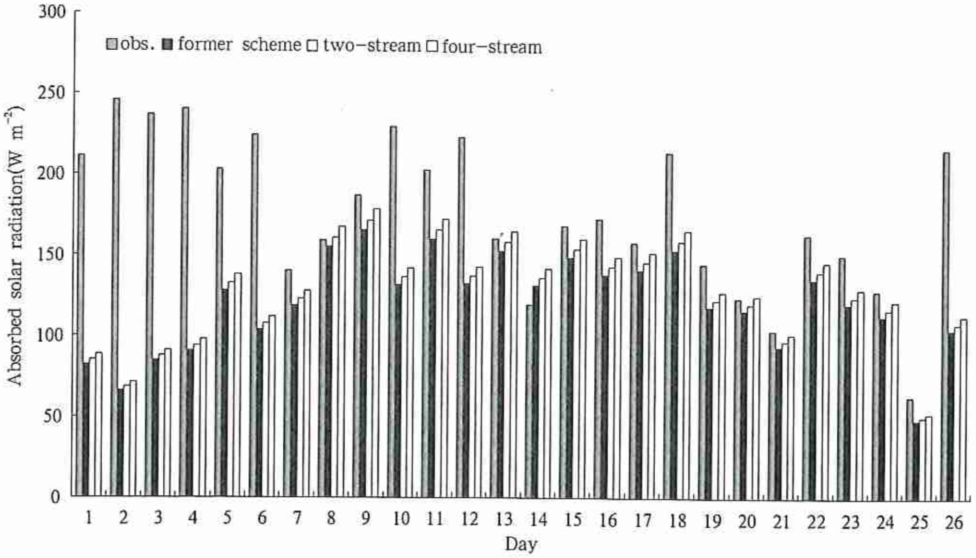

Fig.4. Surface absorbed solar radiation simulated by BATS using the former scheme, the two- and four-stream radiative schemes from July 10 to August 4 in 1998. Observations in the same period are also shown.

evaluated the effect of a modified BATS land surface process model (Zhou et al., 2005). The results from that study showed that the simulated earth absorbed net solar radiation was obviously lower than the observation (see also the "former scheme" results in Fig. 4). Because the four- and two-stream models derived more accurate surface albedo, which directly affects net solar radiation absorbed by land surface, this leads to improved simulations of surface net solar radiation than that using the former scheme.

5. Conclusions

In order to satisfy the requirements of climate models and increase the precision of radiative flux calculations at the interface of the atmosphere and the land surface, we have developed a four-stream model to simulate solar radiation transfer into vegetation. Some parameters of the model are defined by referring to the two-stream model. The basic canopy radiative transfer equation is solved by introducing a four-stream approximation method. Using the two-stream model for reference, the new four-stream model makes the canopy a turbid medium, and makes leaves the basic elements for absorbing and scattering radiation. The four-stream model is appropriate to simulate radiative transfer of full-grown vegetation. Canopy albedo results of the four-stream model are related to the diffuse phase function, G-function, leaf reflectivity, leaf transmission, leaf area index, and the solar angle of incident beams. We tested the simulations with a horizontal leaf through comparisons with simulations of the two-stream model within the canopy. The model is proved successful as it has the same results for canopy albedo at any solar incidence angle and agrees well with the two-stream model results under the horizontal leaf condition.

This paper presents the differences of the two- and four-stream models for incident diffuse radiation and incident beam radiation, given spherical and vertical leaf angle distributions. Simulations indicate that the difference is large when the leaf scattering albedo is large in the NIR band. The difference is very obvious when the leaf angle distribution is vertical and the solar angle is above 25° or 35°.

In order to illustrate the advantage of the four-stream model, the four- and two-stream models are coupled into BATS land surface model. The effect of the two models on BATS simulations is evaluated. The tests indicate that the simulation of the land surface process model coupled with the four-stream model is the best among all the simulations using different radiative transfer models.

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