A Simple Yet More Accurate Model to Calculate Solar Radiative Flux in the Inhomogeneous Atmosphere

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ABSTRACT

A simple yet more accurate semiempirical model is developed to calculate solar radiative flux in the optically inhomogeneous atmosphere. In the model a parameterized expression of spherical reflectance and transmitance of the atmosphere is confirmed, and the weighted single scatter albedo and weighted asymmetric factor are introduced to fit four empirical correction factors responsible for radiative fluxes in the inhomogeneous atmosphere. For both clean and turbid models, there are 120060 sets of radiative flux simulations for accuracy checks of the model, which cover 0–50 cloud optical depths, 0–0.8 surface reflectance, Junge and Log–normal aerosol size distributions, and 0–0.05 imaginary parts of aerosol refractive indexes. In case of the homogeneous atmosphere, standard errors of the 120060 upward fluxes from the present model are 1.08% and 1.04% for clean and turbid aerosol models, respectively; and those of the downward fluxes are 4.12% and 3.31%. In case of the inhomogeneous atmosphere, standard errors of the upward fluxes from the present model are 3.01% and 3.48% for clean and turbid aerosol models, respectively; and those of the downward fluxes are 4.54% and 4.89%, showing a much better accuracy than the results calculated by using an assumption of the homogeneous atmosphere.

Key words: Radiative flux, Inhomogeneous atmosphere, semiempirical model

1. Introduction

A simple yet accurate model to calculate the solar radiative flux is important for the general circulation climate model and some remote sensing applications. Among the simplest and most widely used approximations to the radiative transfer equation are the two–stream approximations. There are different kinds of two–stream approximations (Coakley and Chylek 1975; Joseph and Wiscombe 1976; Liou 1974; Meador and Weaver 1980; Shetter and Weinman 1970). King and Harshvardhan (1986) comprehensively examined the accuracy of various two–stream approximations, and it was concluded that all exiting approximations can not yield good accuracy of reflection, transmission and absorption calculations at all optical depths, solar zenith angles and single scattering albedos for climate model application. For this reason, Qiu (1999) developed a modified Delta–Eddington approximation. The approximation can yield a great improvement of transmission, reflection and absorption calculations in the condition of the optical depth $\tau_t \leqslant 1$, but its accuracy basically is the same as that from Delta–Eddington when $\tau_t > 1$. Because two–stream approximation can not meet more and more high demand of climate model and remote sensing applications, some authors paid great efforts to develop more accurate four–stream approximation (Liou 1974) and four–stream Delta–M approximation (Liou et al. 1988), and they derived analytical solution

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of radiative flux in the condition of the homogeneous atmosphere and the zero surface–reflectance. The surface–atmospheric coupled radiative flux can be expressed in terms of the flux without surface reflection, the surface reflectance, spherical reflection and transmission of the atmosphere. In addition, the reflection and transmission are also needed to calculate surface–atmospheric coupled radiative radiance (Qiu 2001a; Qiu 2001b; Vermote et al. 1997). In this paper, a semiempirical model is developed to calculate the surface–atmospheric coupled radiative flux in the inhomogeneous atmosphere, including a parameterized expression of the spherical reflection and transmission and four correction factors responsible for inhomogeneity of the atmosphere.

2. Semiempirical model of solar radiative flux

For a Lambertian surface, upward and downward solar radiative fluxes, $F^{\uparrow}$ and $F^{\downarrow}$, can be expressed as

$$F^{\uparrow} = F^{\uparrow}_{\rm path} + F^{\downarrow}_{\rm path} T_{\rm S} A_{\rm S} / (1 - R_{\rm S} A_{\rm S}), \tag{1}$$

$$F^{\downarrow} = F^{\downarrow}_{\rm path} / (1 - R_{\rm S} A_{\rm S}), \tag{2}$$

where $A_{\rm S}$ is the surface reflectance; $F^{\uparrow}_{\rm path}$ and $F^{\uparrow}_{\rm path}$ are upward and downward fluxes without surface reflection, respectively; $R_{\rm S}$ and $T_{\rm S}$ are spherical reflectance and transmittance of the atmosphere in the condition of uniform illumination from surface, taking both integrations over azimuth and zenith angles (Qiu 2001a; Vermote et al. 1997)

Let $k_{\rm R}$ indicate the ratio of the upward flux ($F^{\uparrow}_{\rm path}$) without surface reflection in the inhomogeneous atmosphere to the flux ($F^{\uparrow}_{0,\rm path}$) in the homogeneous atmosphere, i.e.

$$k_{\rm R} = F^{\uparrow}_{\rm path} / F^{\uparrow}_{0,\rm path}, \tag{3}$$

similarly, define

$$k_{\rm T} = F^{\downarrow}_{\rm path} / F^{\downarrow}_{0,\rm path}, \tag{4}$$

$$u_{\rm R} = R_{\rm S} / R_{0,\rm S}, \tag{5}$$

$$u_{\rm T} = T_{\rm S} / T_{0,\rm S}, \tag{6}$$

where $F^{\downarrow}_{0,\rm path}$, $T_{0,\rm S}$ and $R_{0,\rm S}$ are the downward flux, spherical reflectance and transmittance for the homogeneous atmosphere, respectively. Then, Eqs.(1) and (2) can be changed as

$$F^{\uparrow} = F^{\uparrow}_{0,\rm path} k_{\rm R} + F^{\downarrow}_{0,\rm path} k_{\rm T} T_{0,\rm S} u_{\rm R} A_{\rm S} / (1 - R_{0,\rm S} u_{\rm R} A_{\rm S}), \tag{7}$$

$$F^{\downarrow} = F^{\downarrow}_{0,\rm path} k_{\rm T} / (1 - R_{0,\rm S} u_{\rm R} A_{\rm S}). \tag{8}$$

$F^{\uparrow}_{0,\rm path}$ and $F^{\downarrow}_{0,\rm path}$ can be calculated by using analytical formation of the 4–stream Delta–M method. Therefore, the remaining problems are how to calculate such six parameters as $R_{0,\rm S}$, $T_{0,\rm S}$, $k_{\rm R}$, $k_{\rm T}$, $u_{\rm R}$ and $u_{\rm T}$. In this paper, they are parameterized by combining the least square technique and the empiric corrections.

$R_{0,\rm S}$ changes in the range from 0 to 1, and it increases with an increase of the optical depth. So, $y = 1 - \exp(-\tau_s)$ (τ_s is the scattering optical depth) is taken as independent variable to parameterize the relationship of $R_{0,\rm S}$ with the optical depth. The parameterization procedure is divided into following three steps:

(1) Using the least square method, confirm the relationship of $R_{0,\rm S}$ with y in the

conservative atmosphere for a given scattering phase function.

(2) Using the least square method, find the relationship of $R_{0,S}$ with the asymmetric factor of the phase function.

(3) The parameterization expression is extended to the case of the absorbing atmosphere through some empiric corrections.

The final parameterization expression of $R_{0,S}$ is

$$R_{0,S} = [(0.93 - 0.507g_0 - 0.374g_0^2)y - (0.608 - 0.259g_0 - 0.286g_0^2)y^2 + (0.4 + 0.27g_0 - 0.542g_0^2)y^3]f_R, \tag{9}$$

$$y = 1 - \exp(-\tau_s), \tag{10}$$

$$f_R = [2 - \exp(-0.0051\tau_s^2)]\tilde{\omega}_0^{22\sqrt{\tau_s}}. \tag{11}$$

$T_{0,S}$ is the sum of the direct transmittance (T_{dir}) and the diffuse transmittance (T_{dif}). Using similar procedure as mentioned above, T_{dir} and T_{dif} are parameterized with the following results:

$$T_{0,S} = T_{dir} + T_{dif}, \tag{12}$$

$$T_{dif} = [(1.05 + 0.72g_0 + 0.187g_0^2)y - (1.65 + 1.69g_0 - 0.973g_0^2)y^2 + (2.13 + 2.65g_0 - 1.96g_0^2)y^3 - (1.31 + 1.7g_0 - 1.51g_0^2)y^4]f_T, \tag{13}$$

$$T_{dir} = 2\int_0^1 \mu\exp(-\tau_t/\mu)d\mu = 0.337\exp(-\tau_t) + 0.89\exp(-2\tau_t) - 0.659\exp(-3\tau_t) + 0.43\exp(-4\tau_t), \tag{14}$$

$$f_T = \exp\left\{-\frac{(1 - 0.65g_0)[0.69\tau_s^4 + (0.12 - 0.1\tilde{\omega}^{\tau_t})\tau_s^5]}{6900 + \tau_s^4}\right\}\tilde{\omega}_0^{1.7\tau_s + 0.42\sqrt{\tau_s}}. \tag{15}$$

where μ_0 is the cosine of solar zenith angle, τ_t and τ_s are the total and scattering optical depths, g_0 and $\tilde{\omega}_0$ are the atmospheric asymmetric factor and single scatter albedo, respectively. For the optical inhomogeneous atmosphere with N kinds of scattering mediums, g_0 and $\tilde{\omega}_0$ are given by

$$g_0 = \frac{1}{\tau_s}\sum_{i=1}^{N} g_{0,i}\tau_{s,i}, \tag{16}$$

$$\tilde{\omega}_0 = \frac{1}{\tau_t}\sum_{i=1}^{N} \tilde{\omega}_{0,i}\tau_{t,i}, \tag{17}$$

where $\tau_{t,i}$ is the optical depth of the ith medium, $g_{0,i}$ and $\tilde{\omega}_{0,i}$ are its asymmetric factor and single scatter albedo, respectively.

It is found from numerical simulations that the effect of an inhomogeneity of atmospheric optical parameters on the radiative flux is weak for the conservative atmosphere, but it can be very significant for the strongly absorbing atmosphere. Therefore, the dependent factors of such parameters as k_R, k_T, u_R and u_T are analyzed according to the simulated flux data, and then a weighted asymmetric factor (g_{top}) and two weighted single albedoes ($\tilde{\omega}_{top}$ and $\tilde{\omega}_{sur}$) are induced to fit the four parameters, which are defined as

$$g_{top} = \frac{\int_0^{\tau_t} g(\tau)\exp(-2\tau)d\tau}{\int_0^{\tau_t} \exp(-2\tau)d\tau}. \quad (18)$$

$$\tilde{\omega}_{top} = \frac{\int_0^{\tau_t} \tilde{\omega}(\tau)\exp(-2\tau)d\tau}{\int_0^{\tau_t} \exp(-2\tau)d\tau}. \quad (19)$$

$$\tilde{\omega}_{sur} = \frac{\int_0^{\tau_t} \tilde{\omega}(\tau_t - \tau)\exp[-2(\tau_t - \tau)]d\tau}{\int_0^{\tau_t} \exp(-2\tau)d\tau}. \quad (20)$$

where $g(\tau)$ and $\tilde{\omega}(\tau)$ are the asymmetric factor and single albedo at the τ optical depth, respectively. The contributions of the upper atmosphere to g_{top} and $\tilde{\omega}_{top}$ are more weighted, and the effect of the lower atmosphere on $\tilde{\omega}_{sur}$ is more important. Based on a lot of tries and comparisons, relationships of k_R, k_T, u_R and u_T with g_{top}, $\tilde{\omega}_{top}$ and $\tilde{\omega}_{sur}$ are empirically confirmed as

$$k_R = \exp(x_1 - x_2), \quad (21)$$

$$x_1 = (3 - \mu_0^2)(\tilde{\omega}_{top} - \tilde{\omega}_0) - 1.2[1 - \exp(-0.41\tau_s)](\tilde{\omega}_{sur} - \tilde{\omega}_0), \quad (22)$$

$$x_2 = 8.3\tilde{\omega}\exp(-0.038\tau_s / \mu_0)(1 - \tilde{\omega}_0)(g_{top} - g_0), \quad (23)$$

$$k_T = \exp(-x_3), \quad (24)$$

$$x_3 = 3\exp(-0.0032\tau_s^2)(0.825 - 0.35\mu_0 + \mu_0^2)(\tilde{\omega}_{top} - \tilde{\omega}_0) + 3.2\mu_0\{1 - \exp[-0.00023(1 + 5\mu_0)\tau_s^2]\}(\tilde{\omega}_{top} - \tilde{\omega}_0) + (2.5 - \mu_0)[1 - \exp(-0.0012\tau_s^2](\tilde{\omega}_{sur} - \tilde{\omega}_0), \quad (25)$$

$$u_R = \exp(x_4), \quad (26)$$

$$x_4 = 2.5(\tilde{\omega}_{sur} - \tilde{\omega}_0) - 1.25(\tilde{\omega}_{top} - \tilde{\omega}_0), \quad (27)$$

$$u_T = \exp(-x_5), \quad (28)$$

$$x_5 = 2.2[1 - \exp(-0.00078\tau_s^2)](\tilde{\omega}_{sur} + \tilde{\omega}_{top} - 2\tilde{\omega}_0). \quad (29)$$

Eqs.(3)–(29) are the present model to calculate solar radiative flux, in which $F^{\uparrow}_{0,path}$ and $F^{\downarrow}_{0,path}$ can be determined by using the 4–stream Delta–M analytical solution.

3. Input parameters in numerical simulations

3.1 *Wavelength and gaseous parameters*

Four MODIS channels of 470, 555, 659 and 865 nm (Kaufman et al. 1997; Tanre et al. 1997) are selected, and molecular scattering and absorbing parameters of the channels are taken from the 1976 US Standard Atmosphere in LOWTRAN7 (Bark et al. 1996).

3.2 *Aerosol parameters*

Figure 1 shows two LOWTTRAN profiles of the 550nm–wavelength aerosol extinction coefficients used in simulations, in which the surface visibilities are 23 km and 5 km, and optical depths are 0.32 and 2.14, respectively. The two profiles are denoted as the clean and turbid aerosol models, respectively.

Table 1 shows the aerosol size distributions and its refractive indexes used in simulations. One of the distribution is Junge given by $n(r)=cr^{-(v^*+1)}$. The selected Junge distributions with $v^*=2$, 3 and 4 are marked as J2, J3 and J4, respectively. For the Junge distribution, the real part of aerosol refractive index is 1.5, and its imaginary parts of 0, 0.01, 0.03 and 0.05 are assumed. Another is the log–normal distribution, given by

$$n(r)=\frac{n_0}{\sqrt{2\pi}\ln\sigma}\frac{1}{r}\exp\left\{-\frac{1}{2}\left[\frac{\ln(r/r_n)}{\ln\sigma}\right]^2\right\}, \tag{30}$$

where r is the particle radii, σ and r_n are log–normal distribution parameters. Table 1 gives parameters of the used four log–normal distributions and aerosol refractive indexes. The models are corresponding to small (particle) rural, large rural, small urban and large urban, presented by Molineaux et al. (1998) and Abdou et al. (1997) respectively.

Aerosol extinction coefficient profiles at the four MODIS channels are determined by using Mie scattering calculations and above aerosol input parameters.

Table 1. Aerosol sized distributions and refractive indexes

Mark	Type	r_n	σ	Refractive index
J2	Junge, $v^*=2$			1.5–0, 0.01, 0.03, 0.05i
J3	Junge, $v^*=3$			1.5–0,0.01,0.03,0.05i
J4	Junge, $v^*=4$			1.5–0,0.01,0.03,0.05i
Ru_S	Small rural	0.03	2.239	1.47–0.0047i
Ru_L	Large rural	0.5	2.512	1.46–0.0033i
Urb_S	Small urban	0.03	2.239	1.453–0.0463i
Urb_L	Large urban	0.5	2.512	1.443–0.0467i

3.3 *Cloud parameters*

The C_1 cloud size distribution, presented by Diermendjian (1969) is selected, and its refractive index is 1.332–0i. The Cloud Optical Depth (COD), marked as τ_c, selects nine values of 0, 0.5, 1.0, 5, 10, 20, 30, 40 and 50. The cloud base heights of 1 km and 2 km and the cloud thickness of 1 km are assumed.

3.4 *Atmospheric layer division and scattering phase function*

Two atmospheric models, homogeneous and 18–layer, are used in all the present numerical simulations. In the 18–layer model, the height steps are 1 km and 2 km from the surface to 6 km and then from 6 km to 30 km, respectively, and in every layer uniform scattering phase function and single scatter albedo are assumed.

3.5 *Solar zenith angle and surface reflectance*

There are selected fifteen solar zenith angles changing from 0° to 70° and with a step of 5°, and the seven surface reflectances of 0.05, 0.1, 0.2, 0.3, 0.4, 0.6 and 0.8.

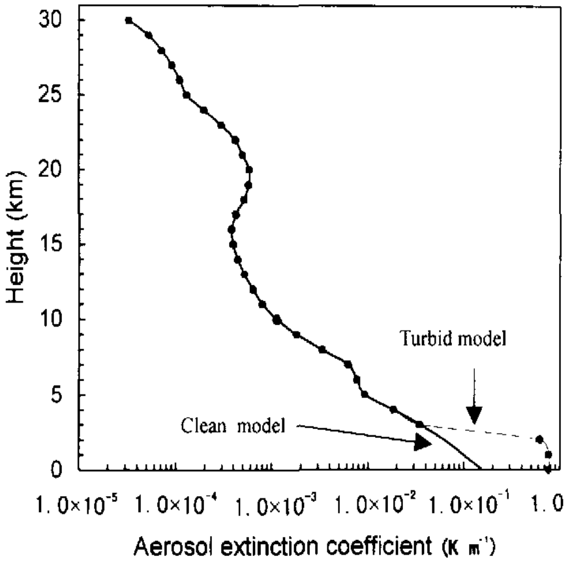

Fig. 1. Vertical profile of the aerosol extinction coefficients at the 550 nm wavelength.

Above input parameters cover wide atmospheric conditions.

4. Numerical simulation results

In the numerical simulations, 4–stream and 32–stream Delta—M codes in DISORT (Stamnes et al. 1988; Wiscombe 1977) are used in calculating radiative fluxes, and the 32–stream results are regarded as the ' true' fluxes. Two standard errors to estimate accuracy of flux calculations are defined as follows:

$$\delta_{R,i} = \sqrt{\sum_{i=1}^{N}(1-F^{\uparrow}_{i,P}/F^{\uparrow}_{i})^2/N} \times 100\%, \quad i=1,2,3,4 \tag{31}$$

$$\delta_{T,i} = \sqrt{\sum_{i=1}^{N}(1-F^{\downarrow}_{i,P}/F^{\downarrow}_{i})^2/N} \times 100\%, \quad i=1,2,3,4 \tag{32}$$

where N is the statistic examples, and meaning of the fluxes $F^{\uparrow}_{i}$ and $F^{\uparrow}_{i,P}$ in four cases is explained in Table 2.

Substituting ' downward flux' from ' upward flux' in Table 2 leads to the meanings of $F^{\downarrow}_{i}$ and $F^{\downarrow}_{i,P}$. Clearly, $\delta_{R,1}$ and $\delta_{T,1}$ denote the standard errors of upward and downward fluxes from the semiempirical model and using $F^{\uparrow}_{0,\mathrm{path}}$ and $F^{\downarrow}_{0,\mathrm{path}}$ from 4–stream Delta–M in the homogenous atmosphere; $\delta_{R,2}$ and $\delta_{T,2}$ have the same definition except for using $F^{\uparrow}_{0,\mathrm{path}}$ and $F^{\downarrow}_{0,\mathrm{path}}$ from 32–stream Delta–M. $\delta_{R,3}$ and $\delta_{T,3}$ stand for the standard errors by assuming the homogeneous atmosphere in the 18–layer atmosphere, and $\delta_{R,4}$ and $\delta_{T,4}$ denote the standard errors of upward and downward fluxes from the present model in the inhomogeneous atmosphere.

Table 2. Meaning of radiative fluxes $F_i^{\uparrow}$ and $F_{i,p}^{\uparrow}$ at the top of the atmosphere

i	$F_i^{\uparrow}$	$F_{i,p}^{\uparrow}$
1	Upward flux from 32–stream Delta–M in the homogeneous atmosphere	Upward flux from the present model in the homogeneous atmosphere, where $F_{0,path}^{\uparrow}$ and $F_{0,path}^{\downarrow}$ are determined from 4–stream Delta–M
2	Same as above	Same as above, except for $F_{0,path}^{\uparrow}$ and $F_{0,path}^{\downarrow}$ from 32–stream Delta–M
3	Upward flux from 32–stream Delta_M in the 18–layer atmosphere	Upward flux from 32–stream Delta–M in the homogeneous atmosphere, same as $F_1^{\uparrow}$
4	Same as above	Upward flux from the present model in the inhomogeneous atmosphere, where $F_{0,path}^{\uparrow}$ and $F_{0,path}^{\downarrow}$ are determined from 4–stream Delta–M

Accuracy of the semiempirical model is analyzed according to Figs. 2–5 and Tables 3–5.

Figures 2 and 3 show the standard errors of upward and downward fluxes for 7 kinds of aerosol size distributions, 0–50 CODs, the cloud base height of 1 km and the clean aerosol model. Input parameters in Figs. 3–4 are the same as in Figs. 2–3, except for the turbid aerosol model. In these figures, cases a, b, c and d are corresponding to 4 kinds of flux simulations shown in Table 2. For 3 kinds of Junge distribution, there are 1680 sets (4 aerosol refractive indexes × 4 wavelengths × 7 surface relectances × 15 solar zenith angles) of flux data for calculating the standard errors; for 4 log–normal distributions, there are 420 sets.

As shown in Fig. 2a, the standard errors of upward fluxes from the present model in the case of the homogeneous atmosphere and the clean aerosol model are all less than 2% for all 7 aerosol size distributions and 0–50 CODs, and they show an enlarging trend with an increase of COD. When COD is larger than 5, the errors are less than 0.7%. When the depth is less than 1, the standard errors are relatively larger, for which the errors of fluxes $F_{0,\mathrm{path}}^{\uparrow}$ and $F_{0,\mathrm{path}}^{\downarrow}$ from 4–stream Delta–M are mainly responsible. When 32–stream Delta–M is used in calculating $F_{0,\mathrm{path}}^{\uparrow}$ and $F_{0,\mathrm{path}}^{\downarrow}$, the standard errors are all less than 0.65% for all CODs (Fig. 2b), implying a satisfactory accuracy of the parameterized spherical reflectance and transmittance in case of the inhomogeneous atmosphere. As shown in Fig. 2c, there can be a very large error in upward flux calculations if the homogeneous assumption is applied in the condition of the true inhomogeneous atmosphere. Usually, the larger COD is, the larger the error is. For example, the standard error of fluxes for the Urb_L model (strongly absorbing aerosol) is up to 17%, when $\tau_c = 50$. But as shown in Fig.2d, there is still a better accuracy in the upward fluxes from the present model for all CODs in the inhomogeneous atmosphere, with the standard error within 4%.

Next, accuracy of the downward flux calculations is analyzed according to Fig. 3. As shown in Fig. 3a, standard errors of the fluxes from present model are within 2.4% for all aerosol size distributions and CODs within 30, and the errors can be up to 8.2% for $\tau_c \geqslant 40$. The similar results can be seen from Fig. 2b. As shown in Fig.2c, if the homogeneous assumption is made in the condition of the true inhomogeneous atmosphere, the flux error can be large when $\tau_c > 10$, especially for $\tau_c = 50$ and strongly absorbing aerosol, the standard error is $>20\%$. But as shown in Fig. 2d, there is still a better accuracy in the downward fluxes from the present model for $\tau_c < 30$ in the inhomogeneous atmosphere, with the standard error within 5%. When COD is very large (for example $\tau_c = 50$), the downward flux at the surface level is very small, and so, even though its relative error is larger, its absolute error can be

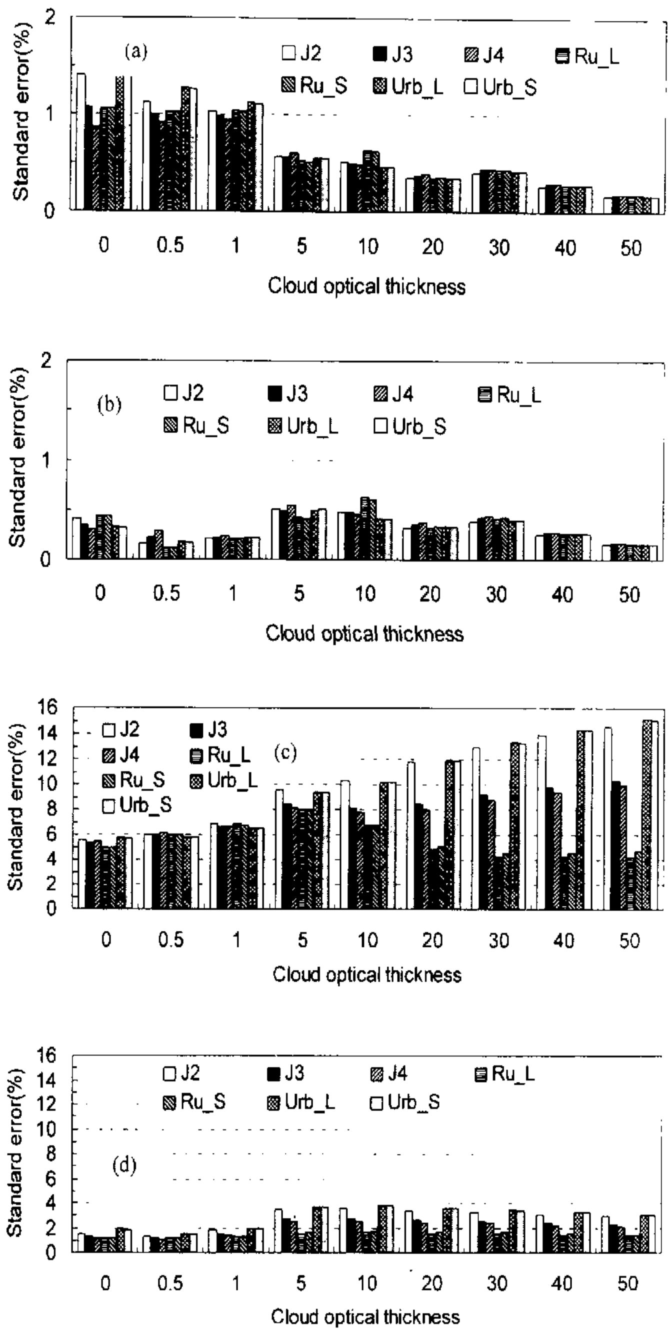

Fig. 2. Standard errors of the upward fluxes for the clean aerosol model and the cloud base height of 1 km.

small.

Figures 4 and 5 are corresponding with the case of the turbid aerosol model, in which the similar conclusion can be found. Standard errors of the upward fluxes from the present model are less than 2% (Fig. 4a) and 5% (Fig. 4d) for all CODs and aerosol size distributions in two cases of the homogeneous and inhomogeneous atmospheres, respectively; those of the downward fluxes are less than 2.9% (Fig. 5a) and 5% (Fig. 5d) when $\tau_c < 30$. It is noted that an assumption of the homogeneous atmosphere can result in a very large error of flux calculations in case of the inhomogeneous and turbid atmosphere, especially for a large COD. As shown in Fig. 4c and Fig. 5c, standard errors of upward and downward fluxes can be up to 85% and 43%, respectively.

Table 3. Percentage standard errors, $\delta_{R,i}$ and $\delta_{T,i}$, of upward and downward fluxes

	Clean aerosol model		Turbid aerosol model	
i	$\delta_{R,i}$	$\delta_{T,i}$	$\delta_{R,i}$	$\delta_{T,i}$
1	1.08	4.12	1.04	3.31
2	0.53	4.09	0.69	3.21
3	11.22	12.25	39.51	24.30
4	3.01	4.54	3.48	4.89

A slightly better accuracy of the present model can be obtained in case of the cloud base height of 2 km. Input parameters in numerical simulations cover two cloud base heights, 9 cloud optical depths, 7 surface reflectances, 4 wavelengths, 15 solar zenith angles, 7 aerosol size distributions, 4 aerosol refractive indexes for Junge distribution and one refractive index for the log–normal distribution. There are 120060 sets of simulations for both clean and turbid aerosol models. Table 3 shows standard errors of the 120060 flux calculations for the two models. Tables 3 and 4 give the maximum errors of upward and downward fluxes for different COD.

As shown in Table 3, in case of the homogeneous atmosphere the standard errors of the 120060 upward fluxes (case $i=1$) calculated by using the parameterized spherical reflectance and transmittance are 1.08% and 1.04% for clean and turbid aerosol models, respectively; and the errors of the downward fluxes are 4.12% and 3.31%. For the inhomogeneous atmosphere, the standard errors of the upward fluxes ($i=4$) from the present semiempirical model are 3.01% and 3.48% for clean and turbid aerosol models, respectively; and those of the downward fluxes 4.54% and 4.89%. In case of the inhomogeneous atmosphere, accuracy of the fluxes calculated by using a homogeneous assumption is much worse than that from the present model, the standard error of upward fluxes increases by about one order of magnitude.

As shown in Tables 4 and 5, the maximum errors of upward and downward fluxes from the present model for the homogeneous atmosphere and $\tau_c = 0$ are 8.38% and 2.17%, respectively; they are 9.16% and 5.82% for the inhomogeneous atmosphere. As $\tau_c = 0$, if $F^{\uparrow}_{0,\mathrm{path}}$ and $F^{\downarrow}_{0,\mathrm{path}}$ from 32–stream Delta–M are used, the maximum error of the upward flux is 2.46%, showing a better accuracy. For the cloudy atmosphere, the maximum error of the upward flux from present model has decreasing (respectively, increasing) trends for the homogeneous (respectively, inhomogeneous) atmosphere when the COD increases. For the inhomogeneous atmosphere with a large COD and strongly absorbing aerosol, a homogeneous assumption can result in the maximum error of 218.96%. When $\tau_c < 30$, the maximum error of the downward flux is < 18%; and when $\tau_c > 30$, it is 23.53%.

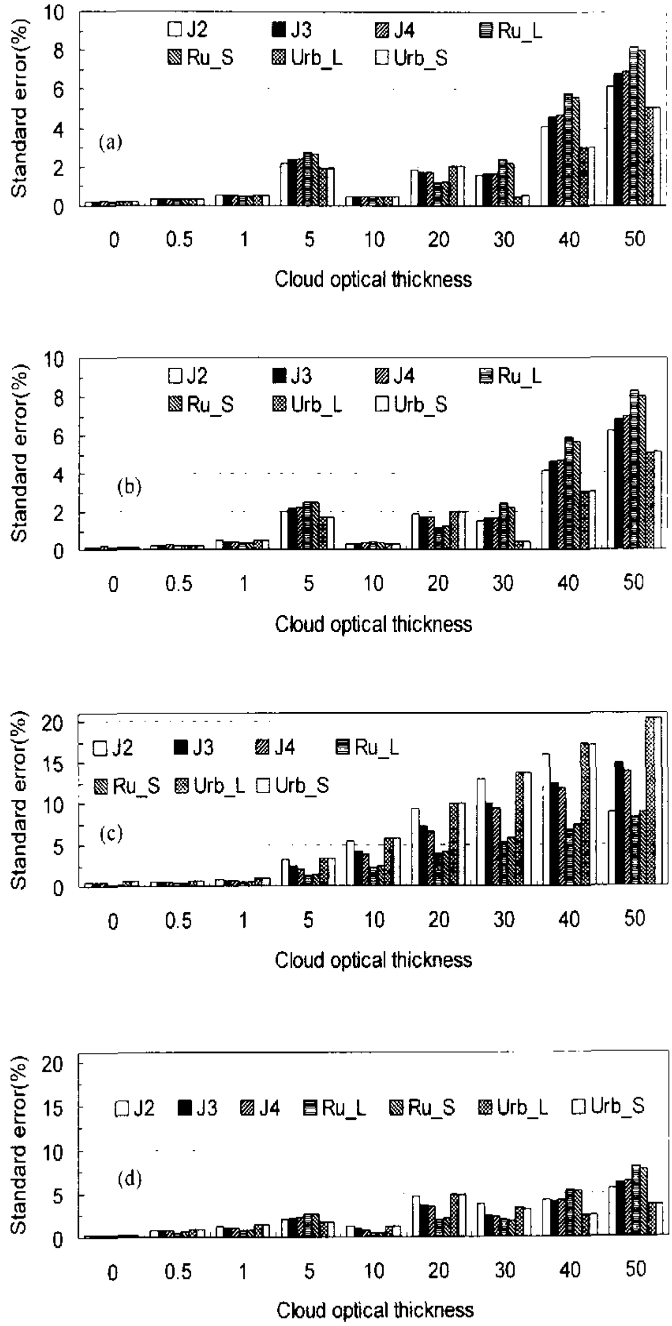

Fig. 3. Standard errors of the downward fluxes for the clean aerosol model and the cloud base height of 1 km.

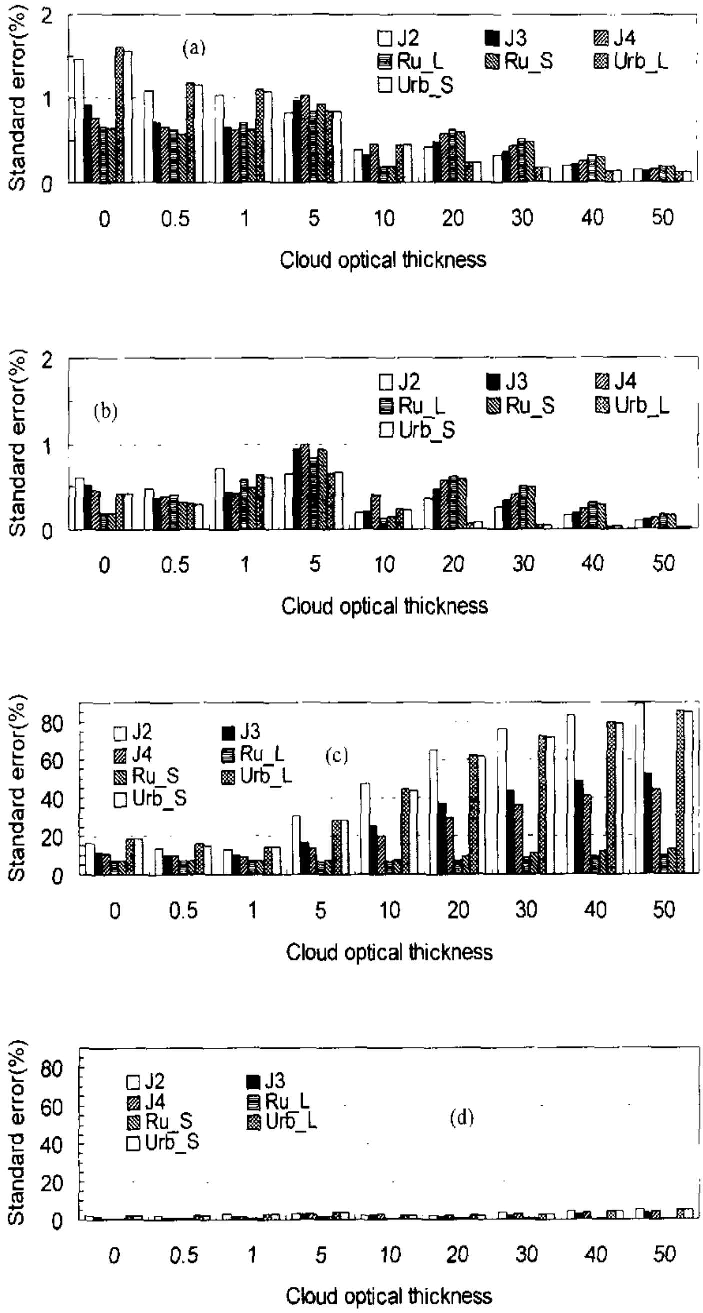

Fig. 4. Standard errors of the upward fluxes for the turbid aerosol model and the cloud base height of 1 km.

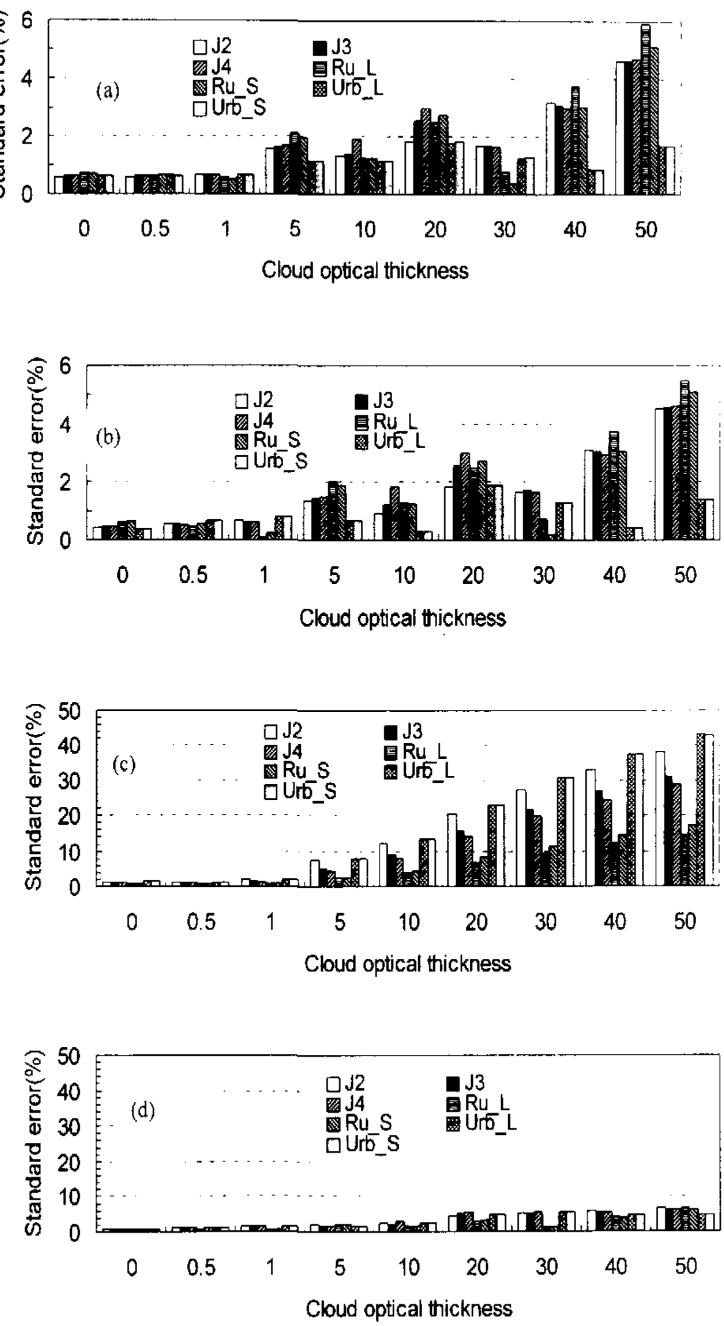

Fig. 5. Standard errors of the downward fluxes for the turbid aerosol model and the cloud base height of 1 km.

Table 4. Maximum percentage error of Upward flux for different cloud optical depths

τ_c	Clean aerosol model				Turbid aerosol model			
	0	$0<\tau_c\leq 10$	$10<\tau_c\leq 30$	$30<\tau_c\leq 50$	0	$0<\tau_c\leq 10$	$10<\tau_c\leq 30$	$30<\tau_c\leq 50$
$i=1$	8.38	5.09	1.81	1.66	4.36	3.81	3.22	1.11
$i=2$	1.02	2.04	1.79	1.54	2.33	3.76	3.17	1.05
$i=3$	14.13	37.45	43.88	46.09	44.64	141.74	202.18	218.96
$i=4$	8.14	13.72	14.65	14.11	9.16	13.34	16.32	18.84

Table 5. Maximum percentage error of Downward flux for different cloud optical depths

τ_c	Clean aerosol model				Turbid aerosol model			
	0	$0<\tau_c\leq 10$	$10<\tau_c\leq 30$	$30<\tau_c\leq 50$	0	$0<\tau_c\leq 10$	$10<\tau_c\leq 30$	$30<\tau_c\leq 50$
$i=1$	1.48	6.48	8.93	23.53	2.17	11.86	10.24	23.30
$i=2$	0.93	5.86	8.57	23.42	2.11	10.77	9.57	23.02
$i=3$	1.66	6.79	15.72	23.67	11.52	25.68	42.48	56.49
$i=4$	1.48	6.49	13.05	23.41	5.82	12.58	17.43	23.24

5. Conclusions

A semi–empirical model to calculate solar radiative flux in the inhomogeneous atmosphere is developed. In the model there is parameterized spherical reflectance and transmittance of the atmosphere, and the weighted single scatter albedo and weighted asymmetric factor are introduced to confirm four empirical factors for flux calculations in case of the inhomoheneous atmosphere.

There are 120060 sets of radiative flux simulations for both clean and turbid aerosol models, covering 0–50 cloud optical depths, 0–0.8 surface reflectance, 0°–70° solar zenith angle, 7 aerosol size distributions and 0–0.05 imaginary part of aerosol refractive index. In case of the homogeneous atmosphere standard errors of the 120060 upward fluxes calculated by using the parameterized spherical reflectance and transmittance are 1.08% and 1.04 for clean and turbid aerosol models, respectively; and the errors of the downward fluxes are 4.12% and 3.31%. For the inhomogeneous atmosphere, the standard errors of the upward fluxes from the semiempirical model are 3.01% and 3.48% for clean and turbid aerosol models, respectively; and those of the downward fluxes 4.54% and 4.89%. In case of the inhomogeneous atmosphere, if an assumption of the homogeneous atmosphere is applied, the standard errors of the upward fluxes are 11.22% and 39.51% for clean and turbid aerosol models, respectively; and those of the downward fluxes 12.25% and 24.30%; and maximum errors of the upward and downward fluxes can be up to 218.96% and 56.49%, respectively, much larger than those from the semi–empirical model. The very large error caused by the homogeneous assumption is usually corresponding with the case of the turbid and strongly absorbing aerosol as well as the large cloud optical depth. The larger the cloud optical depth is, the larger its contribution to the multiple scatter flux component. If the non–absorbing cloud and the strongly absorbing aerosol are assumed in an optically uniform layer, absorption of the cloud to solar radiation can be greatly enlarged through multiple scatter procedure, which can result in a very large error in flux calculations.

In the 4–stream approximation, there are four unknowns to be determined by use of the boundary conditions for the homogeneous (one–layer) atmosphere, and a simple analytical solution can be derived. But for the N–layer atmosphere, there are $4\times N$ unknowns. Generally, an application of the 4–stream approximation for the inhomogeneous atmosphere cannot lead to a simple analytical solution, and a numerical code to determine the unknowns is usually demanded. For the inhomogeneous atmosphere with vertically different single scatter albedo and phase function, the homogeneous assumption can result in a large error in the flux calculations. Based on the analysis of the effect of the atmospheric inhomogeneity on radiative flux, the four empirical correction factors expressed in terms of the weighted single scatter albedo and weighted asymmetric factor are responsible for the inhomogeneity.

The surface–atmospheric coupled radiative flux can be expressed in terms of the flux without surface reflection, the surface reflectance, the spherical reflection and transmission of the atmosphere. Therefore, the parameterized reflection and transmission developed in this paper can be used not only in dividing the contribution of the atmosphere to radiative flux with that of the surface reflection, but also in calculating the surface–atmospheric coupled radiance.

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计算非均一大气条件下太阳辐射通量的一个简单而又精确的模式

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摘　要

发展了一个计算非均一大气条件下太阳辐射通量的一个简单而又精确的模式，其中包括关于大气球反射率与透过率的一个参数化表达式，并引入加权一次散射反照率和加权不对称因子，用于拟合非均一大气条件下计算辐射通量的四个经验订正因子。对清洁和浑浊的两类大气，都具有120060组的辐射通量模拟试验，以检验本模式的精度。这些模拟试验覆盖0–50的云光学厚度、0–0.8地表反射率，Junge和对数正态的气溶胶谱分布、0–0.05气溶胶折射率虚部。在均一大气条件下，由本模式计算的120060组向上通量的标准差对清洁和浑浊两类大气分别为1.08%和1.04%；而向下通量的标准差分别为4.12%和3.31%。在非均一大气条件下，由本模式计算的向上通量的标准差对清洁和浑浊两类大气分别为3.01%和3.48%；而向下通量的标准差分别为4.54%和4.89%，其精度远优于均一假设下的计算结果。

关键词：辐射通量，非均一大气，半经验模式