PARAMETRIZATION OF SOLAR RADIATION FLUXES IN BROKEN CLOUDS

G.A. Titov and T.B. Zhuravleva

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
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We present here a new parametrization of the radiative properties of broken clouds, which uses the effective cloud fraction as a parameter. We have shown that quite a simple and single valued ratio exists between the effective cloud fraction in the visible, N_e^{vis}, and short-wave spectral regions, $N_e^{sw} = f(N_e^{vis})$. We also present in this paper a study of the effects due to random geometry of clouds on the effective cloud amount in the visible region. It is also shown that small variations of the atmospheric aerosol optical thickness $(0 \le \tau_a \le 0.22)$ and of the cloud microstructure may be neglected in the calculations of N_e^{vis} at a fixed value of the cloud optical thickness. Among the advantages of the parametrization proposed there are the possibility of accurately taking into account the effects due to random geometry of clouds and the fact that the development of a numerical model of N_e^{vis} does not require long computer time, and, finally, there is no need in making serious changes into the GCM radiation codes currently in use.

1. INTRODUCTION

In order to improve radiation blocks entering in the general circulation models of the atmosphere (GCMs) methods need to be developed for calculating fluxes of short- and long-wave radiation that would allow for the effects due to stochastic geometry of broken clouds. The development of new radiation blocks should incorporate to a maximum possible degree the advances of modern radiation transfer theory achieved within the model of a plane parallel atmosphere. On the one hand this would certainly save time necessary for developing schemes for parametrization of the radiation properties of broken clouds and, on the other hand, it would minimize the changes to be done for improving the radiation codes for GCMs available.

These requirements will be met if one uses the concept of the effective cloud fraction, N_e, for describing the effects due to the 3-D geometry of broken clouds. The idea of the effective cloud fraction can be explained as follows. The mean radiation flux in broken clouds, F_{bc}, may be represented by a linear combination of the fluxes under the overcast, F_{pp}, and clear sky, F_{clr}, conditions weighted with the factors N_e and $(1 - N_e)$, respectively. Since the values F_{pp} and F_{clr} may be calculated using the radiation codes already available the task reduces to the search for a fast and convenient way of calculating N_e.

Among the first such schemes of parametrization of the radiation properties of cumulus clouds was the scheme proposed in Ref. 1. The idea of this scheme is in the assumption that the radiation properties of a cloud field are equivalent to those of an effective cloud whose geometric size and optical thickness increase with increasing cloud fraction. It is obvious that such a parametrization does not allow for shading and multiple light scattering among clouds, which naturally gives rise to a systematic underestimation of the effective cloud amount at large solar zenith angles.[2]

In Refs. 3 to 7 the reader will find a discussion of a cloud field model in the form of regular spaced clouds of one and the same shape (cylinders, parallelepipeds, and so on) and having the same optical thickness, the so called "chess-board"-model. Welch and Wielicki[6,7] have derived a dependence of N_e, in the visible region, on the cloud fraction N, zenith angle of the Sun, $\xi_{\odot}$, and the aspect ratio $\gamma = H/D$, where H and D are the height and diameter of a cloud. In their calculations they did not take into account the contributions coming from the atmosphere out of clouds and they assumed the albedo of the underlying surface, A_s, to be zero.

A general drawback of such parametrizations is that they do not allow for the stochastic geometry of broken clouds. Since the radiation properties depend nonlinearly on the cloud optical and geometric parameters these parametrizations are unable to adequately describe the radiation transfer in real broken clouds. Moreover, the authors of the above mentioned papers restrict their considerations only to the visible region and do not establish the ratio between the effective cloud fraction in the visible and short-wave regions. Therefore the question of the applicability of those parametrizations to calculations of the integral, over the wavelength spectrum, fluxes of solar radiation still needs to be addressed.

In the research presented in this paper we aimed at developing a new parametrization of the radiation regime in broken clouds that treats the effects due to random geometry of the cloud fields as well as enables us to thoroughly make use of the results obtained in the course of the development of modern radiation codes for GCMs.

We have laid the foundation necessary for developing such a parametrization, namely,

1) we have derived, within the Poisson model of broken clouds, equations for the mean radiance and have developed efficient algorithms for their solution by the Monte Carlo method (see Refs. 8–10). These algorithms enable time saving calculations of the spectral mean fluxes of solar radiation.[11,12] We have also studied in detail the mean, over ensemble of cloud fields, spectral and integral fluxes of short-wave radiation and the absorption of radiation.[10,13–15]

2) we have calculated the mean spectral and integral fluxes of up going and down going radiation for 12 height levels in the atmosphere and 250 different sets of the task input parameters, the latter varying within the following ranges:

– optical thickness of clouds $5 \le \tau \le 60$;

– cloud fraction $0 \le N \le 1$;

– aspect ratio $0 \le \gamma \le 2$, where $\gamma = H/D$, D is the horizontal size characteristic of the clouds. These limits of the aspect ratio, γ, variation enable us to take into account both stratus clouds ($\gamma \ll 1$) and cumulus clouds extended along vertical direction ($\gamma = 2$);

– zenith angle of the Sun $0° \le \xi_{\odot} \le 75°$;

– albedo of the underlying surface A_s varies from 0 for the ocean to 0.8 for a new fallen snow.

2. MODEL AND METHODS OF SOLUTION

The model of the atmosphere and techniques used for calculations of short-wave radiation fluxes in broken clouds are described in detail in Ref. 12. Here we only briefly describe them.

For the atmospheric model we take a combination of horizontally homogeneous layers occupying the height range $0 \le z \le H^{t}_{atm}$, with the meteorological parameters, aerosol concentration, and optical properties being constant within a layer. Layer thicknesses are selected in accordance with the vertical resolution in GCMs (see, for example, Refs. 6 and 17 and the references therein). Thus we have calculated upward and downward fluxes of solar radiation for 12 height levels: 0, 0.5, 1, 1.5, 3, 5.5, 7, 9, 10, 12, 14, and 16 km.

Aerosol model. Within each layer we set the extinction coefficient σ^{a}_{λ} and the single scattering albedo w^{a}_{λ} (here "λ" denotes the radiation wavelength). The vertical structure and the spectral behavior of the optical parameters (σ^{a}_{λ}, w^{a}_{λ}) are taken to be the same as in the cyclic mean model.[18] In our calculations we assume the extinction coefficient to be independent of the wavelength being equal to $\sigma^{a}_{\lambda = 0.69\ \mu m}$. The single scattering albedo was calculated for six wavelengths λ = 0.69, 0.86, 1.06, 1.67, 2.36, and 3.39 μm. The values of w^{a}_{λ} at other wavelengths are calculated using a linear interpolation.

In our calculations we neglect the spectral and height behaviors of the aerosol scattering phase function $g^{a}_{\lambda}(\omega, \omega', z)$ and calculate it by Mie theory formulas[19] for the haze L and wavelength λ = 0.69 μm.

As known the radiation properties of clouds only weakly depend on the aerosol optical parameters (except maybe for such extraordinary situations like dust storms), so the use of a relatively simple aerosol model in calculations is justified.

Model of the gaseous atmosphere. The molecular gaseous components of the atmosphere that absorb the radiation in the visible and near IR regions most strongly are water vapor, carbon dioxide, and ozone. We shall neglect absorption by the ozone in our calculations since the upper boundary of the atmosphere in our model is at the height H^{t}_{atm} = 16 km, well below almost all of the column ozone in the atmosphere.

Solar radiation absorption by atmospheric gases may be accounted for using various models of the atmospheric transmission. As far as we know from the literature available there are no any reliable indications of the advantages of any particular model against others in application to our purposes and because the form of the transmission function is not so important for the parametrization proposed, as will be shown below, we use the transmission functions for the absorption by water vapor and carbon dioxide in the form presented in Refs. 20–22

$$P_{\Delta\lambda} = \exp\left(-\beta_{\Delta\lambda}(w^*)^{m_{\Delta\lambda}}\right) . \tag{1}$$

Here $\Delta\lambda$ is the spectral resolution, (in the spectral region 0.7–3.6 μm $\Delta\lambda$ equals 0.01 μm, on the average); w^* is the equivalent (reduced) mass of the absorbing gas

$$w^* = \frac{1}{\cos\theta} \int\limits_{z_1}^{z_2} \rho(z) \left(\frac{p(z)}{p_0}\right)^{n_{\Delta\lambda}} dz , \tag{2}$$

where $\beta_{\Delta\lambda}$, $m_{\Delta\lambda}$, and $n_{\Delta\lambda}$ are empirical coefficients; $\rho(z)$ and $p(z)$ are the concentration of the absorbing component and the atmospheric pressure at the height z, p_0 = 1 atm; θ is the zenith angle at which the observation is performed. In order to account for the joint effect of absorption by water vapor and carbon dioxide we use the product of the corresponding transmission functions described by formula (1).

Since the profile of an absorbing gas concentration, $\rho(z)$, entering into the Eq.(2) may vary depending on season and geographical zone we take, in our calculations, the moisture profile characteristic of midlatitude summer,[23] while the carbon dioxide is assumed to be uniformly mixed everywhere in the atmosphere, its concentration being equal to 330 ppm.

The meteorological and optical parameters of the atmosphere necessary for making calculations are given in the Table I (each layer is characterized by its upper boundary height).

TABLE I. Profiles of the optical and meteorological parameters of the atmosphere.

Number of the layer	Pressure, hPa	Height, km	ρ, g/m^3	$\sigma^a_{\lambda = 0.69\ \mu m}$	$w^a_{\lambda = 0.69\ \mu m}$
	1000	0.0	–	–	–
1	950	0.5	9.33	$0.768\cdot10^{-1}$	0.862
2	900	1.0	7.95	$0.586\cdot10^{-1}$	0.908
3	850	1.5	6.77	$0.423\cdot10^{-1}$	0.933
4	700	3.0	4.96	$0.188\cdot10^{-1}$	0.947
5	500	5.5	2.09	$0.320\cdot10^{-2}$	0.923
6	400	7.0	0.578	$0.093\cdot10^{-2}$	0.958
7	300	9.0	0.158	$0.055\cdot10^{-2}$	0.967
8	250	10.0	$0.317\cdot10^{-1}$	$0.047\cdot10^{-2}$	0.966
9	200	12.0	$0.36\cdot10^{-2}$	$0.044\cdot10^{-2}$	0.966
10	150	14.0	$0.13\cdot10^{-2}$	$0.022\cdot10^{-2}$	0.975
11	100	16.0	$0.068\cdot10^{-2}$	$0.021\cdot10^{-2}$	0.977

The underlying surface. We assume the underlying surface to reflect incident radiation according to Lambert's law with its albedo being A_s.

Optical model of clouds. We isolate the clouds as a separate layer $H^b_{cl} \le z \le H^t_{cl}$, $H^b_{cl} = 1$ km, and $H^t_{cl} = 1.5$ km. For the optical model of clouds we take random fields of the extinction coefficient $\sigma_\lambda(\mathbf{r})\,\kappa(\mathbf{r})$, single scattering albedo $w_\lambda(\mathbf{r})\,\kappa(\mathbf{r})$, and the scattering phase function $g_\lambda(\omega,\omega',\mathbf{r})\,\kappa(\mathbf{r})$. The mathematical model of the field $(\mathbf{r})$ is constructed based on Poisson fluxes of points on straight lines.[8–10] We assume the optical parameters to be constant within an individual cloud, that is $\sigma_\lambda(\mathbf{r}) = \sigma_\lambda$, $w_\lambda(\mathbf{r}) = w_\lambda$, $g_\lambda(\omega,\omega',\mathbf{r}) = g_\lambda(\omega,\omega')$.

The reasons for taking the Poisson model are as follows.

1) We have derived a closed system of equations for the mean radiance for the case of statistically homogeneous cloud fields and developed efficient algorithms for solving it using the Monte Carlo method[11] (method of closed equations). The accuracy and applicability limits of these equations may be assessed by comparing with the calculations made using numerical simulations of the cloud and radiation fields. The results of such a comparison showed that the equations for mean radiance provide quite an acceptable accuracy[24] and may be used to describe the radiation transfer in any model of statistically homogeneous cloudiness, since one may neglect the influence of the cloud base configuration[25] when calculating mean fluxes and brightness fields.

For the case of nonmarkovian statistics there are formula for splitting the correlation and equations for the moments of radiance proposed in Refs. 26 and 27. However, these equations are difficult for use in practice since the random fields are unknown.

2) The constructive feature of the Poisson model of clouds is in the fact that it allows one to relate its input parameters to the data of field measurements and to give physical interpretation of the calculated results. The comparison[10,28] made between the calculated and experimentally measured statistical properties of the radiation and clouds show that the equations for the mean radiance derived using the Poisson model correctly describe the basic features of the radiation transfer process in cumulus clouds.

Cumulus clouds may have quite fantastic and irregular shapes in a wide variety of scales and are essentially different than the shape of such simple geometric bodies like sphere, cylinder, parallelepiped, and frustum of an overturned paraboloid. Of course, more complicated models are now being developed for a more adequate description of cumulus clouds, but it is a reality that only numerical methods provide a possibility of calculating their radiation properties and they are time consuming. For that reason no parametrization schemes have been created so far based on more complicated though more realistic cloud models.

Method of solution. Our calculations of the mean radiation fluxes in a statistically homogeneous broken cloudiness use the Monte Carlo method developed for solving the system of equations for mean radiance.[10, 11] In addition to such traditionally acknowledged advantages of this method as the controllable accuracy, a possibility of making calculations for cloud fields with the model optical and geometric parameters close to those of real clouds, as well as the possibility of taking into account the effects due to multiple light scattering in clouds, the Monte Carlo method correctly treats the effects due to stochastic geometry of clouds.

In order to improve the efficiency of the algorithm when calculating the spectral fluxes in the spectral region from 0.7 to 3.6 μm we use the method of related tests.[29] When implementing this technique we make use of certain simplifications, which, in their turn, use known spectral behaviors of the cloud optical parameters which in the final result enables us to make the calculations by this algorithm less laborious. The grounds for such simplifications are as follows:

– normally, the extinction coefficient of clouds σ_λ has large magnitude and a neutral spectral behavior; therefore one may surely neglect the spectral variations in the spectral interval {0.7 – 3.6 μm};

– among all the optical parameters the single scattering albedo is most sensitive to the wavelength variation. For that and some other reasons it is worth, in order to allow for its spectral behavior, calculating the values of w_λ for a number of wavelengths thus providing a possibility of linearly interpolating it at any other wavelength λ. For reference wavelengths we have chosen those at which the real, $m(\lambda)$, and imaginary, $\kappa(\lambda)$, parts of the refractive index of water have local minima and maxima at a preset spectral resolution. We also include into the set of these reference wavelengths the wavelength points where the derivatives $\frac{\partial m}{\partial \lambda}$, $\frac{\partial \kappa}{\partial \lambda}$ experience a sharp increase or a decrease.[30] Following these considerations we have chosen the wavelengths at 0.708, 0.760, 0.797, 0.917, 0.980, 1.070, 1.202, 1.426, 1.613, 1.860, 1.875, 1.920, 2.005, 2.224, 2.383, 2.503, 2.660, 2.634, 2.670, 2.706, 2.730, 2.751, 2.798, 2.905, 3.096, 3.199, 3.266, 3.275, 3.298, 3.309, 3.328, 3.340, 3.390, 3.440, 3.510, 3.580, and 3.642 μm for our calculations;

– the single scattering albedo in the spectral subinterval {0.7 – 2.7 μm} is high enough, $w_\lambda \approx 0.9 - 1.0$, and, as a result, the contribution coming from multiple light scattering is large. Therefore we may neglect spectral behavior of the cloud scattering phase function and take it to be a constant $g_{\lambda = 0.706\,\mu\mathrm{m}}(\omega, \omega')$;

– the single scattering albedo of cloud droplets in the spectral subinterval {2.7–3.6 μm} is not very high, $w_\lambda \approx 0.5 - 0.8$. For this reason only several first orders of multiple scattering will contribute to the mean radiation fluxes. Since these orders of multiple scattering are sensitive to variations in the scattering phase function we have calculated the values $g_\lambda(\omega, \omega')$ in this spectral subinterval using a linear interpolation between the scattering phase function values calculated for the above reference wavelengths. In order to properly account for the spectral behavior of the scattering phase function we use special weighting factors.

The model of the atmosphere and the algorithm used for calculating spectral fluxes of radiation, including analysis of its accuracy and efficiency (in the relation to computer time saving) have been considered in detail in Ref. 12.

3. THE EFFECTIVE CLOUD FRACTION: DEFINITION AND SOME PROPERTIES

Let us now give a mathematical definition of the effective cloud fraction and study its basic properties, which we shall use in the discussion below. Since we have homogeneous boundary conditions and assume the cloud field to be statistically homogeneous the mean radiation fluxes are the functions of only one coordinate z.

The net radiation flux at the height z is as follows:

$$F_i(z) = F_i^{\downarrow}(z) - F_i^{\uparrow}(z)\ ,\quad i = \mathrm{clr, bc, pp}, \qquad (3)$$

where $F_i^{\downarrow(\uparrow)}$ are the down and up going radiation fluxes. Here and below, when we deal with the broken clouds, by radiation fluxes we mean the fluxes averaged over an ensemble of cloud fields realization, while omitting the averaging sign for simplicity. As follows from the energy conservation law the absorption $A_i(z_1, z_2)$ of light taking place in the layer (z_1, z_2) (see Fig.1) is

$$A_i(z_1, z_2) = F_i(z_2) - F_i(z_1)\ ,\quad i = \mathrm{clr, bc, pp}. \qquad (4)$$

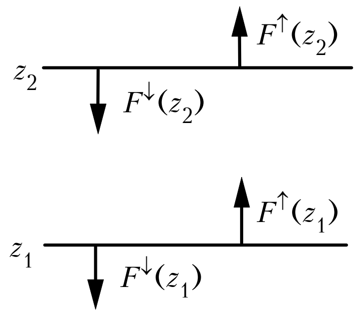

FIG. 1. Schematic representation of the up and down going radiation fluxes.

The net radiation flux $F_{\mathrm{bc}}(z)$ may always be presented in the following form

$$F_{\mathrm{bc}}(z) = N_e(z)\, F_{\mathrm{pp}}(z) + [1 - N_e(z)]\, F_{\mathrm{clr}}(z)\ . \qquad (5)$$

The function $N_e(z)$ entering this expression allows for the 3-D effects in broken clouds and it is just this function that we shall call the effective cloud fraction. Generally speaking this function has no direct geometrical meaning.

If we substitute the equality (3), written for each $i = \mathrm{clr, bc, pp}$, into formula (5) and group separately the terms referring to the down and up going radiation then we have

$$F_{\mathrm{bc}}^{\downarrow(\uparrow)}(z) = N_e(z)\, F_{\mathrm{pp}}^{\downarrow(\uparrow)}(z) + [1 - N_e(z)]\, F_{\mathrm{clr}}^{\downarrow(\uparrow)}(z)\ . \qquad (6)$$

From formulas (5) and (6) we see the first property of the effective cloud fraction that one and the same value enters the expressions for net, down going and up going radiation fluxes at a height z.

The formulas (3)–(6) work both for the spectral and integral fluxes of radiation. Below we shall deal with the integral fluxes in the visible (0.4–0.7 μm) and short-wave (0.4–3.6 μm) regions supplying these quantities with the superscripts "vis" and "sw", respectively. Note also that all the radiation fluxes are in relative units.

3.1. Dependence of the effective cloud fraction on height *z*

According to expressions (5) and (6) we have that

$$N_e(z) = \frac{F_{bc}(z) - F_{clr}(z)}{F_{pp}(z) - F_{clr}(z)} = \frac{F_{bc}^{\downarrow(\uparrow)}(z) - F_{clr}^{\downarrow(\uparrow)}(z)}{F_{pp}^{\downarrow(\uparrow)}(z) - F_{clr}^{\downarrow(\uparrow)}(z)} . \qquad (7)$$

Let us write down the first of the formulas (7) for the height level z_1 and replace the functions $F_i(z_1)$, where i = clr, bc, pp, by the relationships

$$F_i(z_1) = F_i(z_2) - A_i(z_1, z_2) , \quad i = \text{clr, bc, pp} ,$$

which follow from Eq. (4). Then we obtain that

$$N_e(z_1) = \frac{F_{bc}(z_1) - F_{clr}(z_1)}{F_{pp}(z_1) - F_{clr}(z_1)} = \frac{F_{bc}(z_2) - F_{clr}(z_2) - [A_{bc}(z_1, z_2) - A_{clr}(z_1, z_2)]}{F_{pp}(z_2) - F_{clr}(z_2) - [A_{pp}(z_1, z_2) - A_{clr}(z_1, z_2)]} . \qquad (8)$$

From expression (8) naturally follows the second property of the cloud fraction that it does not depend on z if no absorption occurs ($A_i(z_1, z_2) = 0$, i = clr, bc, pp), that is $N_e(z_1) = N_e(z_2)$. However, in the presence of light absorption the equality $N_e(z_1) = N_e(z_2)$ only holds when

$$\frac{F_{bc}(z_1) - F_{clr}(z_1)}{F_{pp}(z_1) - F_{clr}(z_1)} = \frac{F_{bc}(z_2) - F_{clr}(z_2)}{F_{pp}(z_2) - F_{clr}(z_2)} = \frac{A_{bc}(z_1, z_2) - A_{clr}(z_1, z_2)}{A_{pp}(z_1, z_2) - A_{clr}(z_1, z_2)} .$$

We didn't manage to prove the validity of this ratio in the general case, so we may not suppose the effective cloud fraction to be independent of z.

3.2. Ratio between the effective cloud fractions in the visible and short-wave regions.

The fluxes of short-wave radiation can be calculated by formulas (5) and (6) provided that $N_e^{sw}(z)$ is known. One of the ways to calculate the effective cloud fraction is as follows:

– first we calculate the quantities F_{bc}^{sw}, F_{clr}^{sw}, and F_{pp}^{sw} using a fine enough grid of the input parameters;

– then we calculate, by formulas like Eq. (7), the values $N_e^{sw}(z)$ and find simple formulas for interpolating the values $N_e^{sw}(z)$ at the intermediate values of the parameters.

A drawback of this approach is that it is time consuming because each set of the input parameters requires about 450 values of the calculated spectral fluxes. The computer time can essentially be reduced if the function $N_e^{sw} = f(N_e^{vis})$ is known, where the quantity $N_e^{vis}(z)$ is defined similarly to $N_e^{sw}(z)$, that is

$$N_e^{vis}(z) = [F_{bc}^{vis}(z) - F_{clr}^{vis}(z)] \,/\, [F_{pp}^{vis}(z) - F_{clr}^{vis}(z)] . \qquad (9)$$

It is characteristic of the visible region that no absorption by cloud particles occurs while that by aerosol is insignificant. As a result the absorption itself and the differences $[A_{pp}(z_1, z_2) - A_{clr}(z_1, z_2)]$ and $[A_{bc}(z_1, z_2) - A_{clr}(z_1, z_2)]$ are negligibly small as compared to $(F_{pp}(z_2) - F_{clr}(z_2))$ and $(F_{bc}(z_2) - F_{clr}(z_2))$, respectively. Then, as it follows from Eq. (8) one can neglect the dependence of $N_e^{vis}(z)$ upon z and assume that $N_e^{vis}(z) = N_e^{vis}$.

Since the contribution coming from the radiative processes in the visible region to the radiation within the entire short-wave region is large enough and because the effects due to stochastic geometry of clouds do not depend on wavelength, one may suppose that the function $N_e^{sw}(z) = f(z, N_e^{vis})$ could be quite simple and single valued.

Figure 2 presents the effective cloud fraction $N_e^{sw}(z)$ as a function of N_e^{vis}. Every point in this figure presents calculations made using a fixed set of the input parameters. The functions $N_e^{sw}(z)$ and N_e^{vis} have been calculated for the up going (a) and down going (b) radiation at the level of the upper boundary of the atmosphere z = 16 km and at the level z = 0 of the underlying surface, respectively.

In the case of cumulus clouds with the aspect ratio $0.5 \le \gamma \le 2.0$ and $0.1 \le N \le 1.0$ the dependence of $N_e^{sw}(z)$ on N_e^{vis} is well approximated by functions of the following view

$$\tilde{N}_e^{sw}(z) = N_e^{vis}\,(1.06 - 0.06\,N_e^{vis}) , \; 0 \le z \le H_{cl}^{b} ,$$
$$\tilde{N}_e^{sw}(z) = N_e^{vis}\,(0.98 + 0.02\,N_e^{vis}) , \; H_{cl}^{t} \le z \le H_{atm}^{t} , \qquad (10)$$

where $\tilde{N}_e^{sw}$ is the approximate value of the effective cloud fraction. Significant differences between $N_e^{sw}(z)$ and $\tilde{N}_e^{sw}(z)$ are observed at large values of the underlying surface albedo ($A_s > 0.4$). In these cases the values F_{pp}, F_{clr} and F_{bc} are close and the quantity is determined with large error.

Let $\tilde{F}_{bc}^{sw}$ be the net fluxes calculated by formula (5), in which the value $N_e^{sw}(z)$ is replaced by $\tilde{N}_e^{sw}(z)$, then

$$\tilde{F}_{bc}^{sw}(z) = \tilde{N}_e^{sw}(z)\, F_{pp}^{sw}(z) + [1 - \tilde{N}_e^{sw}(z)]\, F_{clr}^{sw}(z). \qquad (5')$$

Let the accuracy of calculations of the net fluxes by formula (5′) be as follows

$\Delta F^{\rm sw}_{\rm bc}(z) = 100\% \, [\tilde{F}^{\rm sw}_{\rm bc}(z) - F^{\rm sw}_{\rm bc}(z)] \, / [F^{\rm sw}_{\rm bc}(z)]$.

Formulas of the type (5') also apply to calculations of the up and down going short-wave radiation fluxes.

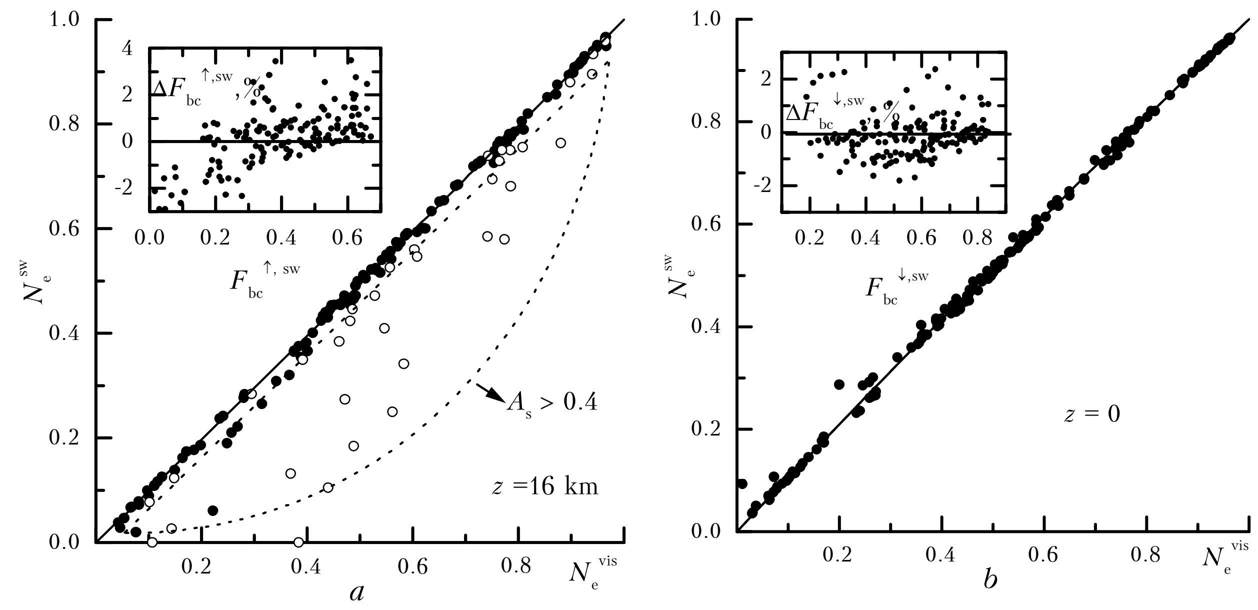

FIG. 2. The dependence of $N_{\rm e}^{\rm sw}(z)$ *on* $N_{\rm e}^{\rm vis}$ *and relative error* $\Delta F_{\rm bc}^{\downarrow(\uparrow),\rm sw}(z)$ *in calculations of the up going (a) and down going (b) radiation fluxes at the heights* z = 16 km *and* z = 0.

The data presented in Fig. 2 show that the values $|\Delta F_{\rm bc}^{\downarrow(\uparrow),\rm sw}(z)|$ do not exceed 3–4%. The same is true for except for very infrequent cases of $|\Delta F^{\rm sw}_{\rm bc}(z)|$ when it reaches 5–6%. It should be noted here that large errors in calculations of $\tilde{N}_{\rm e}^{\rm sw}$ do not lead to correspondingly large errors in the short-wave radiation fluxes reconstructed, since at high values of the underlying surface albedo the quantities $F^{\rm sw}_{\rm bc}(z)$, $F^{\rm sw}_{\rm pp}(z)$ and $F^{\rm sw}_{\rm clr}(z)$ (and correspondingly the values $F_{\rm bc}^{\downarrow(\uparrow),\rm sw}(z)$, $F_{\rm pp}^{\downarrow(\uparrow),\rm sw}$ and $F_{\rm clr}^{\downarrow(\uparrow),\rm sw}$) only slightly differ from each other, so that any of the values or may be taken for $F^{\rm sw}_{\rm bc}(z)$.

4. CLOUD FRACTION IN THE VISIBLE REGION

Since now we have established the view of the function $N_{\rm e}^{\rm sw} = f(N_{\rm e}^{\rm vis})$ the task of calculating $N_{\rm e}^{\rm sw}$ reduces to the determination of $N_{\rm e}^{\rm vis}$. Formulas for calculating $N_{\rm e}^{\rm vis}$ in regular array of clouds are presented in Refs. 6 and 7. However, the effects due to finite size of clouds like, in particular, multiple light scattering among clouds are nonlinear functions of the distance between the clouds. The question may be raised, in this connection, as to whether these formulas are applicable to cloud fields with the stochastic geometry of clouds. In order to answer this question, we show in Fig. 3 the data on $N_{\rm e}^{\rm vis}$ obtained using the model of a regular cloud field[6] and the Poisson model of broken clouds. The comparison made in this figure shows that the neglect of the cloud stochastic geometry under conditions of large zenith angles of the Sun and low cloud fractions ($N \le 0.4$) can lead to both overestimation (by 10% at $\gamma = 0.5$) and underestimation (by 20% at $\gamma = 2$) of the up going radiation fluxes, $F_{\rm bc}^{\uparrow,\rm vis}$.

Thus we may summarize that the models which neglect the random geometry of broken clouds can result in large errors in the calculated mean radiation fluxes.

Unfortunately, we have not managed to derive formulas for calculating $N_{\rm e}^{\rm vis}$ within the frameworks of the Poisson model of broken clouds. One of the possible ways to resolve this situation with the determination of the effective cloud fraction is to develop a numerical model. To achieve this task one should undertake the following steps:

– to calculate the quantities $F^{\rm vis}_{\rm bc}$, $F^{\rm vis}_{\rm clr}$ and $F^{\rm vis}_{\rm pp}$ on a sufficiently dense grid with respect to every input parameter;

– to calculate $N_{\rm e}^{\rm vis}$ by formula (9);

– to derive interpolation formulas for calculating the effective cloud fraction at intermediate values of the input parameters.

Time required for computing the numerical models of $N_{\rm e}^{\rm vis}$ is determined by the number of input parameters. In addition to the above mentioned parameters like the optical thickness of clouds τ, cloud fraction N, aspect ratio γ, zenith angle of the Sun $\xi_{\text{Ä}}$, and albedo of the underlying surface A_s, the radiation properties of clouds also depend on the optical properties of aerosol and cloud microphysics.

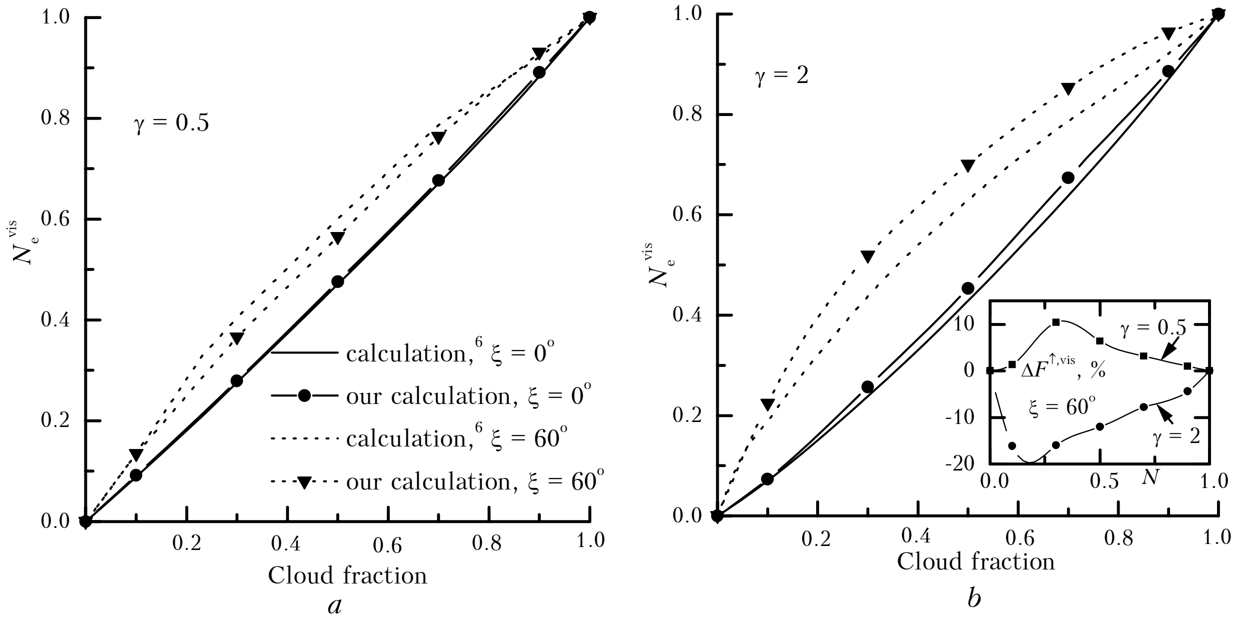

FIG. 3. The effective cloud fraction in the visible region calculated using the Poisson model and the model of regularly distributed clouds[6] *at* $\tau = 49$ *and single scattering albedo* $w = 0.999$.

TABLE II. Influence of the atmospheric aerosol optical thickness on the mean up and down going fluxes calculated using two sets of the input parameters: $A_s = 0.0$, $\gamma = 2$; *the values* τ, N, $\xi_{\text{Ä}}$ *are given in the Table;* $\tau_a^* = 0.11$.

τ, N, $\xi_{\text{Ä}}$	$\tau = 15$; $N = 0.1$; $\xi_{\text{Ä}} = 0°$		$\tau = 5$; $N = 0.3$; $\xi_{\text{Ä}} = 75°$	
Fluxes	$F_{bc}^{\uparrow,vis}(\tau_a)/F_{bc}^{\uparrow,vis}(\tau_a^*)$, $z = 1.5$ km	$F_{bc}^{\downarrow,vis}(\tau_a)/F_{bc}^{\downarrow,vis}(\tau_a^*)$, $z = 1$ km	$F_{bc}^{\uparrow,vis}(\tau_a)/F_{bc}^{\uparrow,vis}(\tau_a^*)$, $z = 1.5$ km	$F_{bc}^{\downarrow,vis}(\tau_a)/F_{bc}^{\downarrow,vis}(\tau_a^*)$, $z = 1$ km
$\tau_a = 0$	0.032/0.033	0.968/0.967	0.32/0.31	0.68/0.69
$\tau_a = 0.22$	0.040/0.041	0.960/0.957	0.32/0.33	0.66/0.65

Optical thickness τ_a of the atmospheric background aerosol is small as compared to the optical thickness of clouds (in our model $\tau_a = 0.11$). Therefore it is admissible to neglect its variability and use some average value N_e^{vis} when calculating $\tau_a^* - N_e^{vis}(\tau_a^*)$. Let $F_{bc}^{\downarrow(\uparrow),vis}(\tau_a^*, z)$ be the radiation fluxes calculated by formulas similar to formulas (6), in which the value $N_e^{vis}(\tau_a)$ is replaced by $N_e^{vis}(\tau_a)$. The calculational results given in Table II show that the difference between $F_{bc}^{\downarrow(\uparrow),vis}(\tau_a, z)$ and $F_{bc}^{\downarrow(\uparrow),vis}(\tau_a^*, z)$ is small at τ_a being between 0 and 0.22 and $\tau_a^* = 0.11$. This clearly demonstrates the fact that relatively small variability of the atmospheric aerosol optical thickness may be ignored when making calculations of N_e^{vis}.

Consider now the dependence of N_e^{vis} on the microphysical properties of clouds. It is obvious that one should expect the highest sensitivity of N_e^{vis} to the cloud microstructure variations at a low optical thickness of clouds.

In Table III are presented the values of N_e^{vis} calculated at a constant τ using different scattering phase functions of clouds, like C_1 cloud (mean cosine of the scattering angle $\bar{\mu}_1 = 0.86$), C_3 ($\bar{\mu}_3 = 0.81$), and C_6 ($\bar{\mu}_6 = 0.89$) (see Ref. 19). The optical thickness of clouds in these calculations was taken to be the same for all cloud types. Since variations of N_e^{vis} are small the variations of the mean radiation fluxes are insignificant (≈1–2%) and the effect of the microstructure variations on the value of N_e^{vis} may also be neglected in calculations.

TABLE III. Influence of the cloud microstructure on N_e^{vis} at $\gamma = 2$, $\xi_{\text{Ä}} = 0°$, $A_s = 0.0$; *the values* τ *and* N *are given in the Table.*

Cloud type	$\tau = 5$, $N = 0.5$	$\tau = 15$, $N = 0.1$
C_1	0.436	0.067
C_3	0.44	0.069
C_6	0.435	0.065

Thus we have just shown that the effective cloud fraction is a function of the five input parameters, τ, N, γ, $\xi_{Á}$ and A_s. The values of these parameters used when constructing the numerical model of N_e^{vis} are as follows

– cloud fraction $N = 0$; 0.1; 0.3; 0.5; 0.7; 0.9; 1.0;

– aspect ratio $\gamma = 0$; 0.2; 0.4; 0.6; 0.8; 1.0; 1.5; 2.0;

– solar zenith angle $\xi_{Á} = 0$; 20; 40; 60; 80°;

– albedo of the underlying surface $A_s = 0$; 0.3; 0.6; 0.9;

– optical thickness of clouds $\tau = 5$; 10; 15; 20; 40; 60.

This set of values of the input parameters makes up 4340 combinations. To make the storage and processing of the calculational data easier we have created a database. The values of N_e^{vis} at intermediate values of the parameters N, γ, $\xi_{Á}$, A_s, τ are then calculated using linear interpolation. The accuracy of N_e^{vis} calculations by interpolation formulas is about 3–4% in the entire range of the parameters variation.

In Refs. 2, 31, and 32 one can find a thorough discussion of the dependence of $F_{bc}^{\downarrow(\uparrow),vis}$ and their partial derivatives on the optical and geometric parameters of clouds and upon the conditions of illumination as well as certain physical interpretation of the facts revealed. However, the results discussed in these papers have been obtained using only a limited set of the values of input parameters that describe only some basic regularities of the radiation transfer in broken clouds.

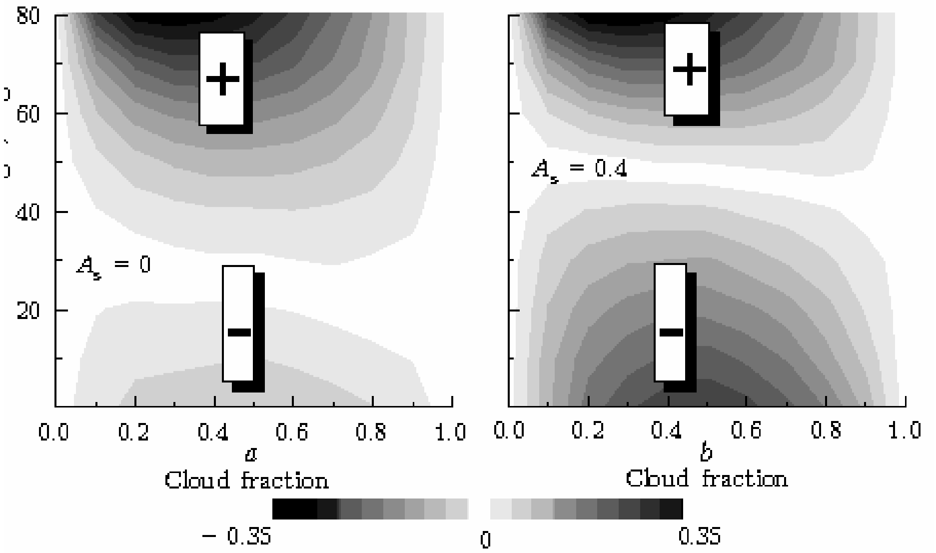

FIG. 4. Illustration to the influence of the Sun zenith angle and cloud fraction on the value of N_e^{vis} at $\gamma = 2$ and $\tau = 15$ and different values of the underlying surface albedo $A_s = 0.0$ (a) and $A_s = 0.4$ (b).

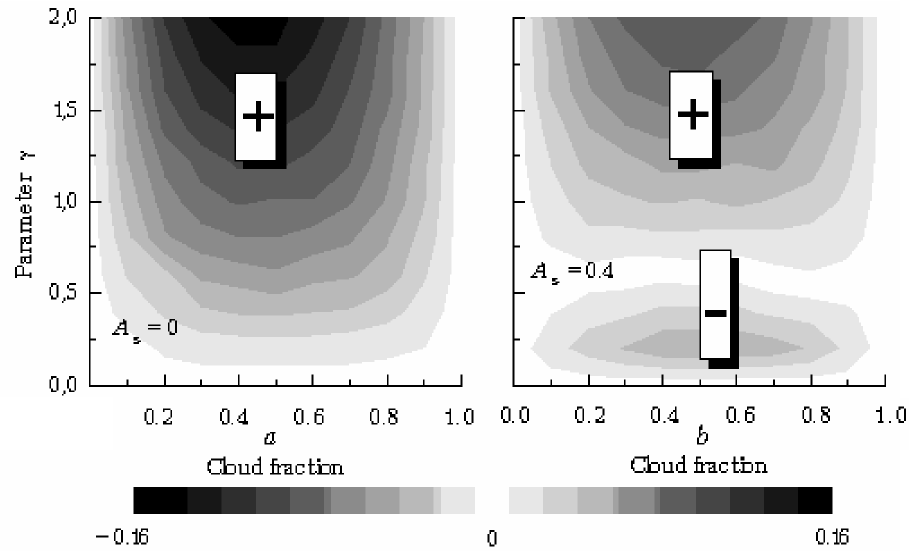

FIG. 5. The dependence of N_e^{vis} on the cloud fraction and aspect ratio γ at $\tau = 15$ and $\xi_{Á} = 60°$ and $A_s = 0.0$ (a) and $A_s = 0.4$ (b).

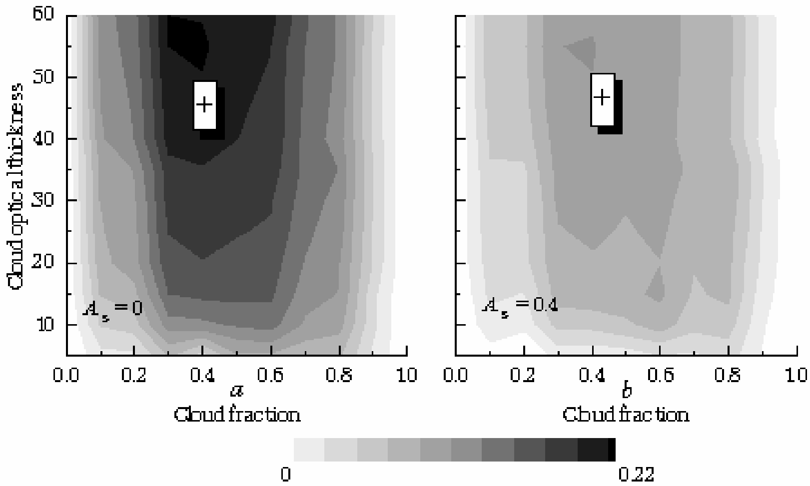

FIG. 6. Illustration to the influence of the cloud optical thickness and cloud fraction on N_e^{vis} *at* $\gamma = 2$, $\xi_A = 60°$ *and* $A_s = 0.0$ *(a) and* $A_s = 0.4$ *(b).*

Numerous calculations we have performed when developing the numerical model of N_e^{vis} enable us to analyze the influence of each of the input parameters N, γ, ξ_A, A_s, τ on the radiation properties of broken clouds. For illustration, in Figs. 4 to 6 is shown the difference $\Delta N_e = N_e^{vis} - N$, which is indicative of the distinctions between radiation fluxes in cumulus clouds ($\gamma \approx 1$) and in equivalent stratus clouds ($\gamma \approx 0$). By equivalence we mean that the clouds differ only by the aspect ratio, other parameters being the same. Symbols "+" and "–" in these figures denote the values obtained at $\Delta N_e > 0$ and $\Delta N_e < 0$, respectively. White regions in the figures correspond to the case when ΔN_e is close to zero.

5. CONCLUSIONS

We have developed a new parametrization of the radiation regime of statistically homogeneous broken clouds whose basic feature is the use of effective cloud fraction N_e. Its basic properties are as follows: 1) one and the same value of N_e is used for calculating net fluxes as well as for calculating the down going and up going fluxes; 2) in the case when absorption occurs in the atmosphere the effective cloud fraction is a function of height z while in the absence of atmospheric absorption the cloud fraction may be considered to be independent of height, $N_e(z) = N_e = \text{const}$.

We have shown that quite a simple and single valued ratio exists between the cloud fraction values in the visible and short-wave spectral regions $N_e^{sw} = f(N_e^{vis})$. It is also shown in this paper that: a) the neglect of the influence of the stochastic geometry of broken clouds can lead to a 10 to 20% error in calculations of the mean radiation fluxes; b) small variations of the atmospheric aerosol optical thickness ($0 \le \tau_a \le 0.22$) and of the cloud microstructure may be neglected in the calculations discussed.

The effects produced by large particles and those due to the phase composition of clouds need for further investigations.

As to the advantages of the parametrization proposed it is worth mentioning that

1. the use of such a parameter as the effective cloud fraction enables one to accurately account for the effects due to random geometry of clouds;

2. the existence of a simple dependence $N_e^{sw} = f(N_e^{vis})$ reduces the task of calculating the short-wave radiation fluxes to calculations of N_e^{vis};

3. the development of a numerical model for that does not require long computer time;

4. there is no need in making serious changes into the GCMs radiation codes currently in use.

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