BRIGHTNESS FIELD OF REFLECTED SOLAR RADIATION UNDER CONDITIONS OF BROKEN CLOUDS. PART II. CALCULATED RESULTS

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Solar radiative transfer is treated in a three-layer cloudy-aerosol atmosphere located over a Lambertian reflecting underlying surface. Mathematical expectation and variance of the intensity of reflected solar radiation, modulated by broken clouds, are investigated as functions of the cloud optical parameters, cloud type, solar zenith angle, and albedo of the underlying surface. It is shown that the effects caused by random geometry of cloud field may produce significant quantitative and qualitative differences in the mathematical expectation and variance of radiation intensity in cumulus and stratus clouds.

Monte Carlo algorithms for calculating the mean and correlation function of the intensity of reflected solar radiation in a three–layer cloudy–aerosol atmosphere over a Lambertian reflecting underlying surface have been developed in Ref. 1. In the present paper, we use these algorithms to investigate the dependence of mathematical expectation and the variance of reflected solar radiation intensity on cloud type, cloud optical parameters, solar zenith angle, and surface albedo.

The top of the atmosphere was assumed to be located at an altitude of 20 km. It coincides with a receiver altitude. Above 20 km, the aerosol and molecular scattering coefficients are vanishing and are thus neglected. The optical thicknesses ($\tau_{a,1}$, $\tau_{a,2}$) and the single scattering albedos ($\lambda_{a,1}$, $\lambda_{a,2}$) of the subcloud (Λ_1) and above–cloud (Λ_2) aerosol layers were chosen for the background model of continental aerosol,[2] for which $\tau_{a,1} = 0.1$, $\tau_{a,2} = 0.02$, and $\lambda_{a,1} = \lambda_{a,2} = 0.879$. Computations were made for a wavelength of 0.69 μm. The scattering phase function of aerosol layers was for Deirmendjian's haze L model,[3] while the cloud scattering phase function was for Deirmendjian's C1 cloud.[3]

Computations were made for a unitary parallel flux of solar radiation incident on the top of the atmosphere. The solar incidence was specified by the zenith ($\xi_\otimes$) and azimuthal ($\varphi_\otimes = 0°$) angles. The receiver had the field–of–view angle $\alpha = 10^{-3}$ rad, and spatial orientation of its optical axis was specified by the zenith (θ) and azimuthal (φ) angles. The absolute values can be obtained by multiplying the numerical results by $S_\lambda \cos\xi_\otimes$, where S_λ is the spectral solar constant. Cloud optical characteristics in the visible depend on wavelength only weakly, so that numerical results can be used to estimate the statistics of the reflected solar radiation in a sufficiently wide spectral interval.

The statistical characteristics of visible solar radiation were computed simultaneously for a set of zenith (θ = 0, 10, 20, 30, 40, 50, 60, 70, and 80°) and azimuthal (φ = 0, 30, 60, 90, 120, 150, and 180°) angles as well as for the surface albedos A_s = 0, 0.2, 0.4, 0.6, 0.8, and 0.9. These last values cover the entire range of the Earth's surface albedos (from ocean surface to that covered with fresh snow). Since the radiation field is symmetrical about the plane of solar vertical, we can restrict our consideration to $1 \le \varphi \le 180°$. The relative computation error was within 1–5% for most of the computation.

Figure 1 shows the mean intensity of reflected solar radiation modulated by cumulus $\langle I_{Cu}\rangle$ and equivalent stratus $\langle I_{St}\rangle$ clouds. Here and below, the equivalence is taken to mean that cumulus and stratus cloud fields have the same optical and geometrical characteristics and differ only in the parameter $\gamma = H/D$ (H is the cloud layer thickness), which is approximately 1 for cumulus and does not exceed 10^{-2}–10^{-3} for stratus.[4] In the computations we used the model of cloud field simulated with the help of the Poisson point process on straight lines. The cloud field so obtained was statistically homogeneous and anisotropic, and the cloud base was on the average a square. The latter fact implies that in the XOY plane the average optical characteristics of clouds possess mirror symmetry about straight lines passing through an arbitrary point in azimuthal directions φ = 0, ±45, and 90°. Obviously, at $\xi_Ä = 0°$ the average field $\langle I_{St}\rangle$ itself must possess the same symmetry. This statement is supported graphically by Fig. 1*a*. For horizontally homogeneous stratus clouds and overhead sun, $\langle I_{St}\rangle$ is insensitive to the azimuthal viewing angle φ (Fig. 1*b*); slight variations with φ are caused by computation error. Attention is drawn to the fact that $\langle I_{St}\rangle$ is maximum at nearly zero zenith viewing angle and decreases with θ; for cumulus, the reverse is true. Qualitatively, this means that $\langle I_{St}\rangle$ and $\langle I_{Cu}\rangle$ may behave differently with θ.

For nearly overhead sun, the mean fluxes of direct radiation are almost insensitive to cloud type. Because the scattering phase function is strongly forward–peaked, radiation exiting through the sides of cumulus contributes primarily to the transmission. As a result, for most zenith viewing angles θ the reflected radiation satisfies inequality $\langle I_{Cu}\rangle < \langle I_{St}\rangle$; for the given model parameters, this occurs at $\theta < 60°$ (Fig. 1). At large $\xi_\otimes$, the incident solar radiation is attenuated by the sides of cumulus clouds; therefore, the mean unscattered radiation flux in cumulus can be significantly less than that in equivalent stratus, while for diffuse fluxes the opposite is true. For this reason, at $\xi_\otimes = 60°$ the inequality $\langle I_{Cu}\rangle > \langle I_{St}\rangle$ can be valid (Fig. 2).

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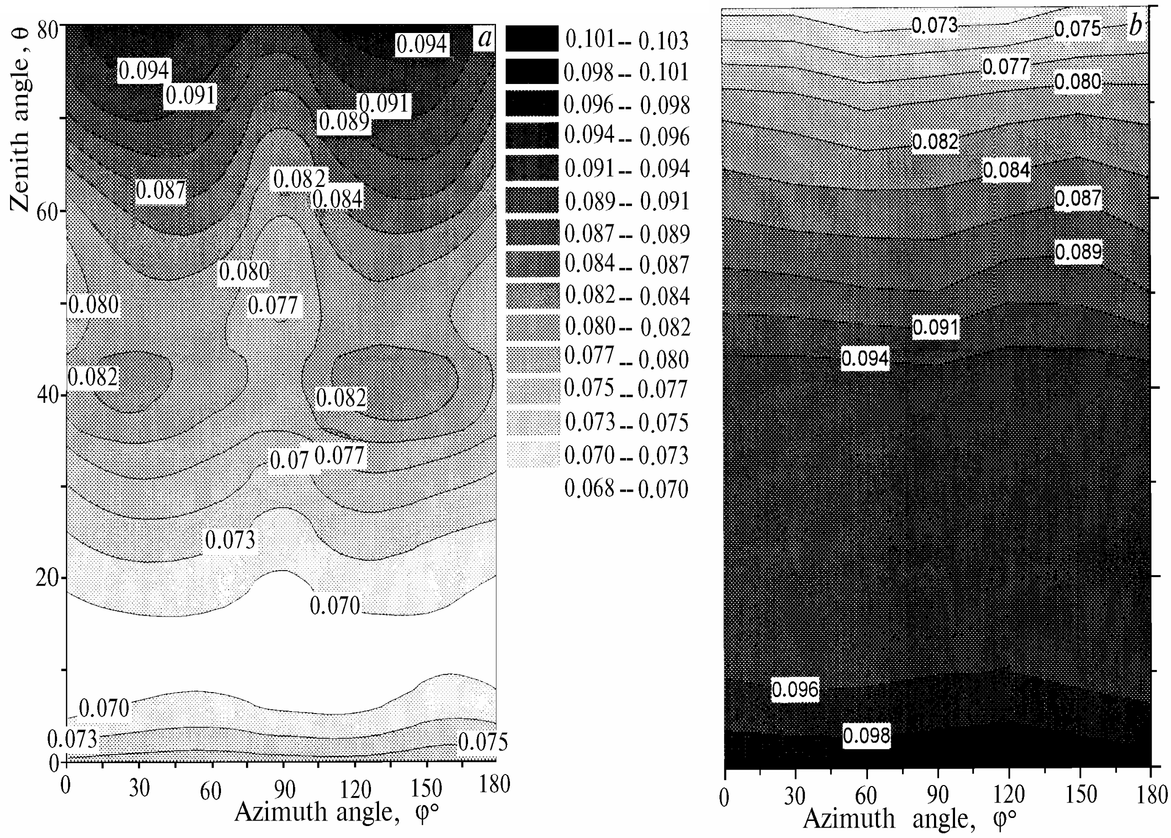

FIG. 1. Mean brightness field of reflected solar radiation at $\xi_{\otimes} = 0°$ for $N = 0.5$, $\sigma = 30$ km^{-1}, $H = 0.5$ km, and $A_s = 0$: a) cumulus clouds ($\gamma = 1$), b) stratus clouds ($\gamma = 0$).

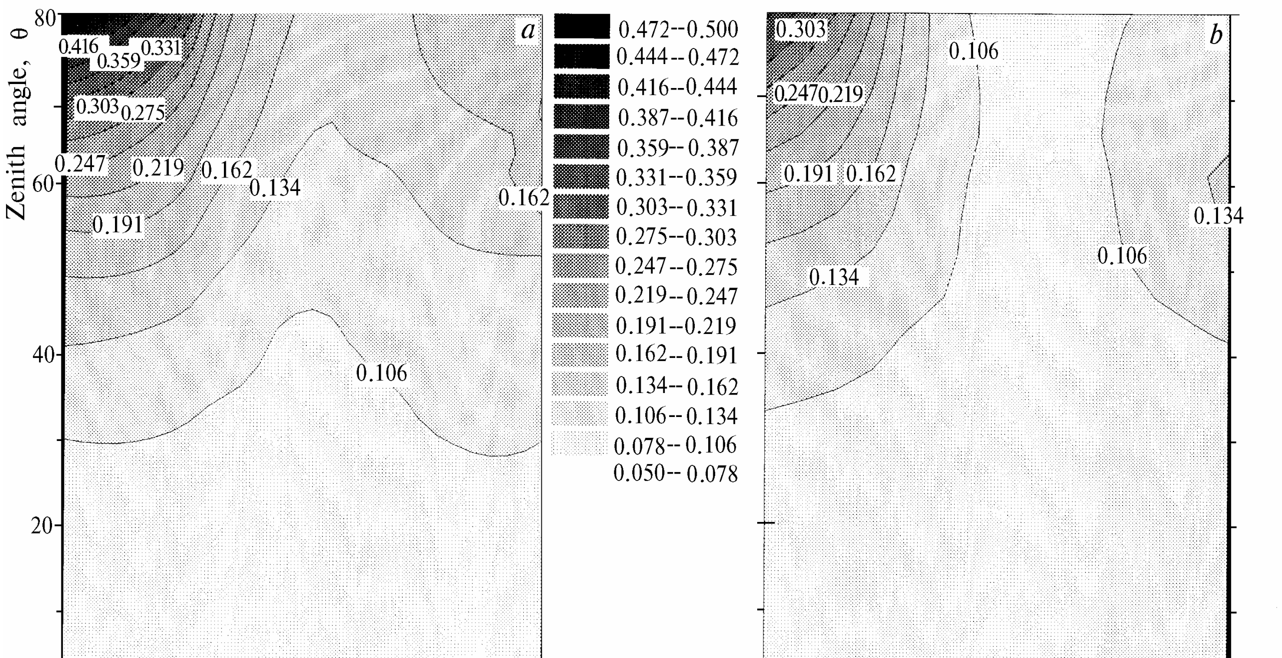

FIG. 2. Mean brightness field of reflected solar radiation at $\xi_{\otimes} = 60°$ for $N = 0.5$, $\sigma = 30$ km^{-1}, $H = 0.5$ km, and $A_s = 0$: a) cumulus clouds ($\gamma = 1$), b) stratus clouds ($\gamma = 0$).

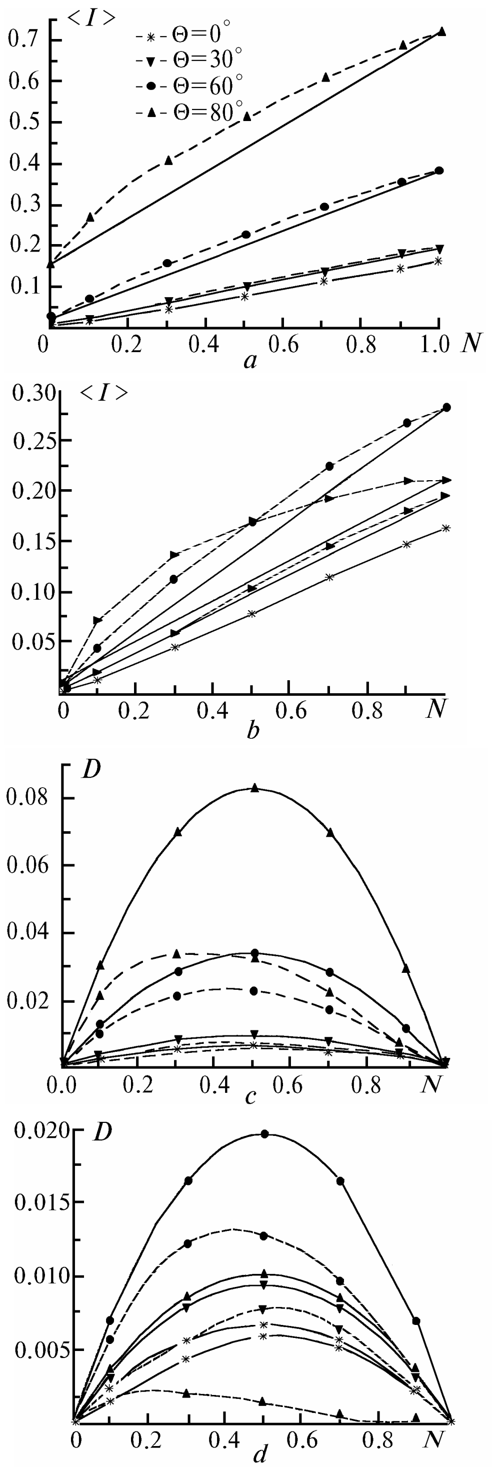

FIG. 3. Dependence of the mean (a and b) and variance (c and d) of the reflected solar radiation intensity on cloud fraction N *with* $\sigma = 30\ \text{km}^{-1}$, $H = 0.5$ km, $D = 0.5$ km, *and* $A_s = 0$ *at different zenith (θ) and azimuthal (φ) viewing angles: a) and b)* $\varphi = 0°$, *c) and d)* $\varphi = 180°$. *Here and in figures 4–7* $\xi_\otimes = 60°$, *solid lines refer to stratus clouds, and dashed lines indicate cumulus.*

The mean intensity $\langle I_{St}\rangle$ is known to be a linear function of cloud fraction, i.e., $\langle I_{St}\rangle$ varies with N independently of θ (Figs. 3*a* and *b*). In the case of cumulus cloud, $\langle I_{Cu}\rangle$ depends nonlinearly on N, and the character of this dependence is extremely sensitive to θ. The mean intensity $\langle I_{Cu}\rangle$ is most sensitive to cloud fraction for small N and large θ, when the partial derivative $\partial\langle I_{Cu}\rangle/\partial N$ is maximum. For stratus clouds, the variance D_{St} is symmetrical about $N = 0.5$, and the magnitude of its maximum depends strongly on the viewing angle (Figs. 3*c* and *d*). The intensity variance in cumulus D_{Cu} is significantly less than D_{St}, the variance in stratus. This is because a finite field of view of a receiver for arbitrary cumulus cloud field realization records not only radiation from cloud tops, but also from sides of individual clouds, so that the radiation field fluctuations are on the average smoothed out. The maximum of D_{Cu} is located in the vicinity of $N \sim 0.5$ at small θ and shifts toward smaller cloud fractions as θ increases. This D_{Cu} behavior is because the effect of cumulus cloud sides on radiative transfer is also viewing angle dependent.

The radiation reflected from the surface can be scattered by clouds, and its considerable portion is then reflected backward to the surface. Some portion of this radiation propagates through cloud gaps ("holes"). The aerosol atmosphere is optically thin, so this radiation may contribute significantly to the brightness field of solar radiation reflected by the system "atmosphere–surface". Simple geometric considerations show that this contribution will be most significant at viewing angles close to zenith. These angles increase with decreasing cloud fraction and increasing horizontal cloud size, as in either case the average solid angle, within which a cloud gap ("hole") is seen from the ground, also increases. Results shown in Fig. 4 confirm the aforesaid. Indeed, at $\varphi = 0°$, as A_s increases from 0 to 0.9, the mean intensity $\langle I_{Cu}\rangle$ in the direction $\theta = 30°$ is nearly doubled, while at $\theta = 80°$ the amount of increase is ~10%. The radiation reflected from the surface smoothes out somewhat the brightness contrast between clouds and gaps ("holes"), so that the variance decreases as A_s increases. Obviously, contribution of radiation reflected from the surface n times will be proportional to the quantity

$$A_s^n\, \overline{Q}\, \overline{A}_d^{\,n-1}, \tag{1}$$

where $\overline{Q}$ is the mean transmission of the total solar radiation at the surface level (prior to reflection), $\overline{A}_d$ is the albedo of the atmosphere provided that its bottom is illuminated by a diffuse radiation flux reflected from the surface. Since $\overline{Q}$ and $\overline{A}_d$ are cloud type dependent, the underlying surface may contribute to the brightness field differently in cumulus or in equivalent stratus cloud system. At $\varphi = 180°$ and arbitrary values of θ, $\langle I_{St}\rangle$ depends on A_s stronger than $\langle I_{Cu}\rangle$. It is obvious from Eq. (1) that this contribution will sharply decrease with increase of the reflection order n and that the radiative statistical characteristics will depend on surface albedo almost linearly (Fig. 4). For this reason, qualitatively the radiative field will not strongly depend on surface albedo, and henceforth we restrict ourselves to the case $A_s = 0$. Radiation reflected from the surface smoothes somewhat the brightness contrast between the clouds and gaps ("holes"), so that the variance decreases with increasing A_s.

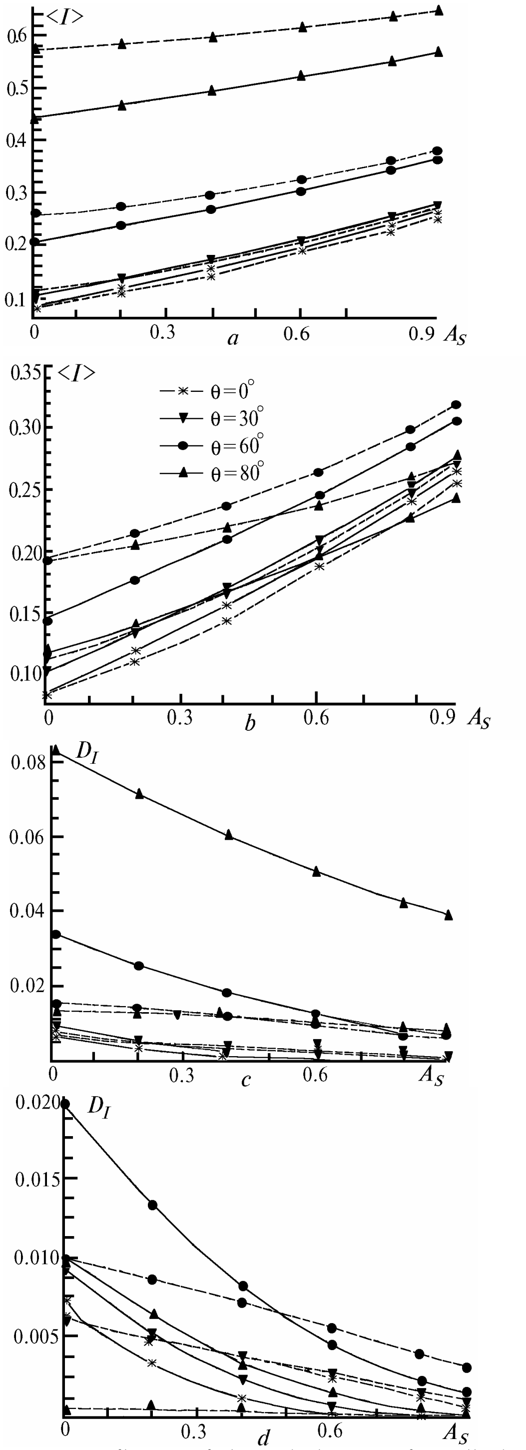

FIG. 4. Influence of the underlying surface albedo A_s on the mean (a and b) and variance (c and d) of reflected solar radiation intensity with $N = 0.5$, $\sigma = 30$ km^{-1}, $H = 0.5$ km, *and* $D = 0.25$ km *at different zenith* (θ) *and azimuthal* (φ) *viewing angles : a) and c)* φ = 0°, *b) and d)* φ = 180°.

Increasing the extinction coefficient σ from 15 to 120 km^{-1} causes the mean intensities $<I_{Cu}>$ and $<I_{St}>$ to increase by a factor between 1.5 and 2.0 (Fig. 5), a fairly clear and well–known result. The same result is obtained as the cloud fraction increases by ~0.1–0.2 (Fig. 3). Therefore, the mean intensities are more sensitive to the cloud fraction variations than to the extinction coefficient variations. Increasing the extinction coefficient enhances the difference between reflected solar radiation intensities coming from clouds and cloud gaps; as a result, the intensity variance grows both for cumulus and stratus clouds.

Vast statistics for cloud microstructure and a variety of cloud models are available now that differ both in the parameters employed and in the shapes of particle size distribution functions. In this regard, the question arises: how much the choice of a model affects the radiative characteristics of broken and stratus clouds?

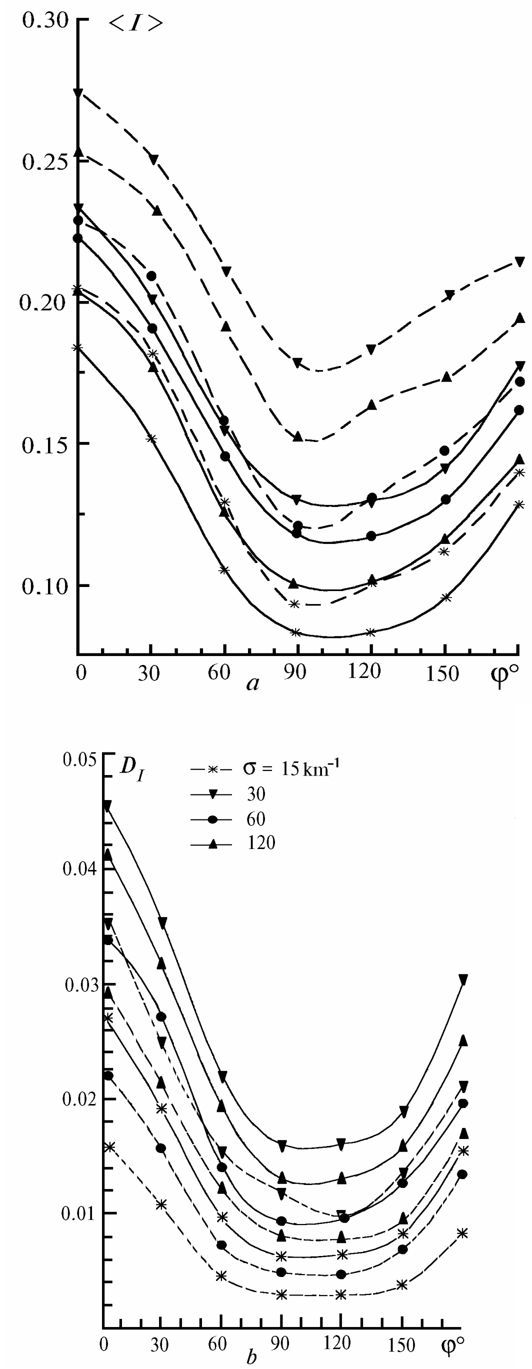

FIG. 5. Dependence of the mean (a) and variance (b) of reflected solar radiation intensity on azimuthal viewing angle φ *with* $N = 0.5$, $H = 0.5$ km, $D = 0.25$ km, *and* $A_s = 0$ *at* θ = 60° *as function of the extinction coefficient* σ.

We used three cloud models that differed in the parameters of modified gamma distribution $n(r)$. The model parameters are listed in Table I; here r_{eq} and r_{mean} are the equivalent and mean radii, N_0 and w are the mean values of droplet concentration and water content, respectively. C1 and C3 cloud models were borrowed from Ref. 3, and C6 model was borrowed from Ref. 5.

TABLE I.

Cloud model	a	α	γ	r_m, μm	r_{eq}, μm	r_{mean}, μm	N_0, cm^{-3}	w, g/m^3
C1	2.373	6	1	4	6.0	4.7	100	0.0625
C3	5.5556	8	3	2	2.2	2.0	100	0.00377
C6	0.0005	2	1	20	49.4	29.1	1	0.251

In the visible range, the extinction coefficient σ is related to r_{eq} by the expression[6]

$$\sigma = 3\,w / 2\,\rho\, r_{eq}\,, \tag{2}$$

where ρ is the density of water, in g/m^3, and

$$r_{eq} = \int\limits_0^\infty n(r)\, r^3\, dr \Big/ \int\limits_0^\infty n(r)\, r^2\, dr. \tag{3}$$

As seen from Eq. (3) and Table I, for a fixed water content the extinction coefficient varies by more than a factor of twenty for different cloud models. The scattering phase functions, computed from the Mie theory for a wavelength of 0.69 μm, also may differ significantly. Particularly, at a zero scattering angle, the difference between the scattering phase functions may exceed two orders of magnitude.

First we estimate the effect of scattering phase function (for fixed extinction coefficient and, hence, optical thickness) on the brightness field of reflected solar radiation. For a higher degree of forward–peaking, the mean intensity at large zenith viewing angles θ increases and decreases in viewing directions close to the nadir (Fig. 6). For the given model parameters, multiple scattering cannot smooth out completely the effects induced by the phase function, so that the intensity mean and variance are very sensitive to the phase function variations both for cumulus and stratus clouds.

With the water content fixed, changes in the mean intensity and its variance are due to the variations in the scattering phase function and the extinction coefficient (optical thickness). The significant decrease (by more than a factor of twenty) in the optical cloud thickness with increase of r_{eq} produces notable reduction in the mean reflected solar radiance (Fig. 7). Obviously, neglect of the cloud microphysical properties may lead to significant misestimates of statistical characteristics of reflected solar radiance; this should be kept in mind, e.g., when interpreting the satellite data on radiation budget of cloud fields. The radiation fluxes are functionals of the mean intensity; therefore, the general circulation model (GCM) parameterization of cloud radiative properties must include, as basic parameters, not only cloud fraction and water content, but also a characteristic cloud droplet size. We note that large particle clouds (with particles of radii > 40–50 μm) may significantly reduce the amount of reflected solar radiation in the visible and near–IR spectral ranges.[7]

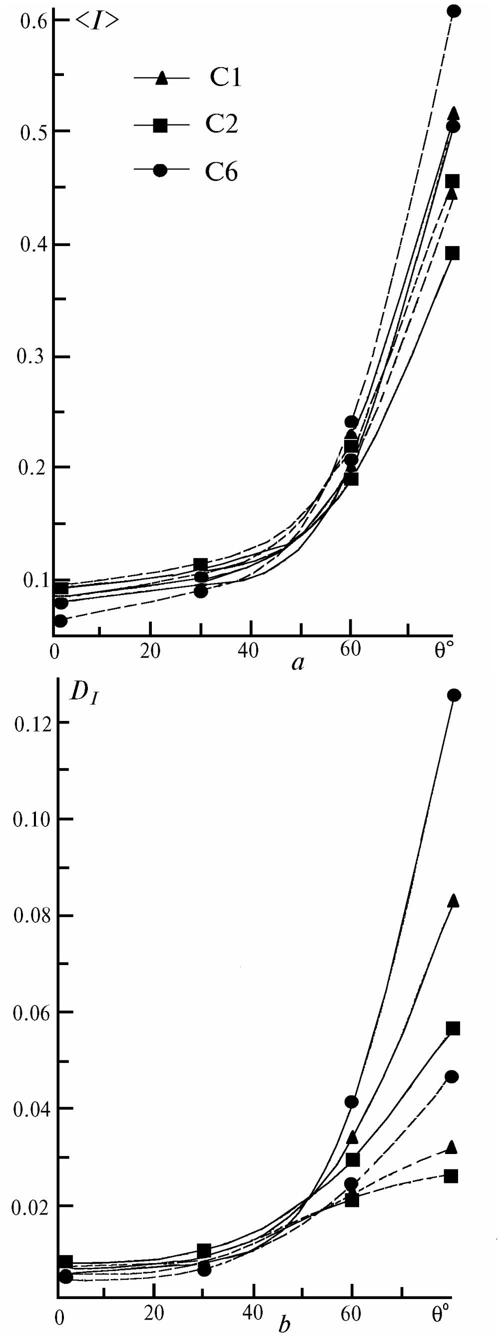

FIG. 6. Dependence of the mean (a) and variance (b) of reflected solar radiation intensity on zenith viewing angle θ with scattering phase functions for C1, C3, *and* C6 *cloud models,* $N = 0.5$, $\sigma = 30^{-1}$ km, $H = 0.5$ km, $D = 0.5$ km, *and* $A_s = 0$ *at* $\varphi = 0°$.

Decreasing the mean optical thickness and less forward–peaked scattering phase function (i.e., passing on from C3 to C6 cloud model) enhances the transmission of cloudy layer and thus increases the contribution of subcloud optically most dense aerosol and of underlying surface to the brightness field of reflected solar radiation. Since for the given model parameters the subcloud aerosol layer and the stratus and cumulus clouds for C6 model contribute nearly equally to the mean reflected intensity, the intensity variances vanish.

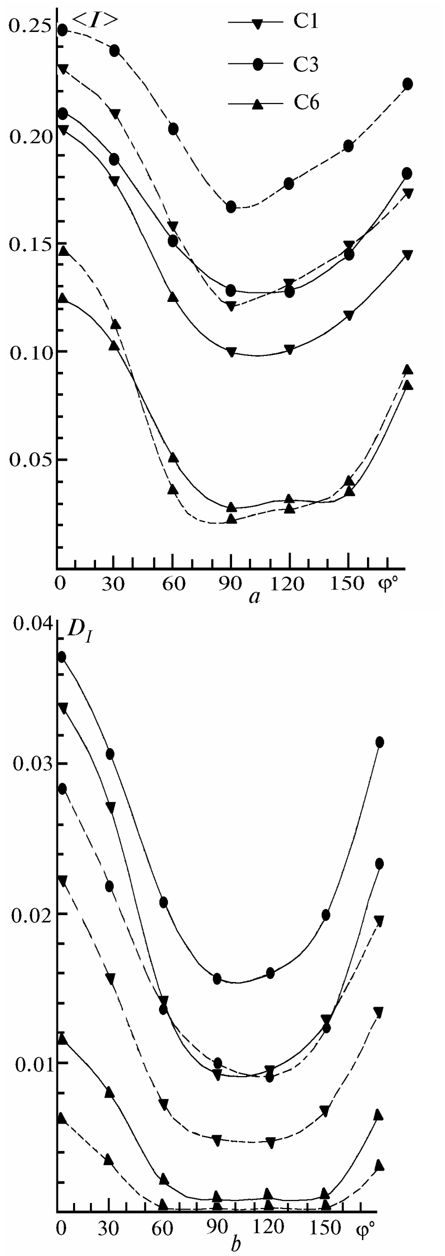

FIG. 7. Dependence of the mean (a) and variance (b) of reflected solar radiation intensity on azimuthal viewing angle φ for a fixed water content with $w = 0.12$ g/m^3, $N = 0.5$, $H = 0.5$ km, $D = 0.5$ km, and $A_s = 0$ at $\theta = 60°$ as functions of the parameters of modified gamma distribution.

CONCLUSION

The mathematical expectation and variance of the intensity of reflected solar radiation, modulated by cumulus and equivalent stratus clouds, have been investigated as functions of cloud optical parameters, solar zenith angle, and surface albedo. The equivalence is taken to mean that the above–indicated cloud types have the same optical and geometrical characteristics and differ only in the mean horizontal size. It is shown that the effects caused by random geometry of cloud fields may lead to considerable, both qualitative and quantitative, differences in mathematical expectation and variance of the intensity in cumulus and stratus clouds.

Among the key parameters governing the solar radiative transfer are the cloud fraction and the mean (characteristic) horizontal cloud size. In particular, the mean intensity varies by a factor between 1.5 and 2.0 when the cloud fraction changes by ~0.1–0.2 or when the extinction coefficient (optical thickness) changes by approximately a factor of eight. This indicates that the partial derivative of the mean intensity with respect to cloud fraction, $\partial\langle I\rangle/\partial N$, is approximately 2–3 orders of magnitude larger than the derivative $\partial\langle I\rangle/\partial\sigma$. We note that $\partial\langle I\rangle/\partial D$ and $\partial\langle I\rangle/\partial N$ agree to within an order of magnitude.[8]

For small underlying surface albedo, the mean intensity in cumulus remains still sensitive to phase function variations even when the extinction coefficient (optical thickness) is sufficiently large. This makes the angular distribution of solar radiation, reflected by cumulus cloud field, essentially anisotropic and, generally speaking, it cannot be described by a simple relation. As the underlying surface albedo increases, the dependence of the mean and variance of the intensity on cloud optical parameters, solar zenith angle, and cloud type becomes weaker.

The intensity mean and variance for cumulus are extremely sensitive to the choice of the cloud microphysical parameters (cloud model). Given the water content is fixed, the intensity mean and variance may diminish by approximately an order of magnitude (by more than a factor of eight) as the cloud droplet equivalent radius increases from 2.2 μm to 49.4 μm. This circumstance must be taken into account, e.g., in interpretation of the data of optical remote sensing of the cloudy atmosphere.

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