THE EFFECT OF MICROPHYSICAL PARAMETERS ON THE RADIATIVE CHARACTERISTICS OF BROKEN CLOUDS

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Seven models of clouds with different size distribution functions of cloud particles are analyzed. The effect of microphysical parameters of cloud models on radiative characteristics of broken clouds is investigated. It is shown that variations of the cloud microstructure can result in significant variations of the mean radiation fluxes.

At present a large amount of the statistical information about the microstructure of real clouds has been accumulated. The cloud droplet size distribution depends on season, geographic location, and cloud shape as well as it may significantly alter within the cloud.[1-3] Since the droplet size spectrum depends on many factors, the construction of the cloud model is rather complicated problem. In practice various cloud models, which differ not only in the parameters[4] but also in the shape of the cloud droplet size distribution function,[5,6] may be employed for solving many important applied problems. In this connection the question arises: how strong the choice of the model affects the radiative characteristics of clouds.

Eight cloud models describing various shapes of clouds and their geographic location were analyzed, and the effect of cloud microstructure on the values of backscattering (β) and extinction coefficients was estimated in Ref. 5. It was shown that the optical and, therefore, the radiative properties of clouds are primarily determined by the large particles. For example, after truncation of the spectrum at 25 μ, i.e., after 10% decrease in total concentration β decreases by a factor of two, while neglecting droplets whose radii are less than 10 μ (decrease of concentration by 70%) results in the change of the parameter β by not more than 10%.

The sensitivity of the radiation transmitted and reflected by clouds to various droplet size distributions was investigated in Ref. 7. The parameters of distributions were chosen in such a way that six cloud models differed only in the shape of the scattering phase function. It followed from the calculated results that the radiative characteristics depended strongly on the microstructure despite the identical cloud optical thicknesses (τ). The effect of microstructure altering with altitude within the cloud on the transmitted and reflected fluxes of solar radiation in the visible range was estimated in Ref. 8. Three different vertically uniform droplet size distributions were employed closely resembling those observed near the base, in the middle, and at the top of the cloud. Results of calculations have shown that the radiative properties of clouds differed significantly reaching 23% for transmitted and 7% for reflected fluxes even for the fixed water capacity of clouds.

The horizontally homogeneous cloud layers were considered in Refs. 5, 7, and 8. The purpose of this paper is the evaluation of the effect of the cloud microphysical parameters on the radiative characteristics of broken clouds.

CLOUD MODELS

Seven cloud models were employed which differed in the parameters of the modified gamma distribution:

$$n(r) = ar^{\alpha}\exp\left(-\frac{\alpha}{g}\left(\frac{r}{r_m}\right)^{\gamma}\right), \qquad (1)$$

where $n(r)$ is the distribution function, r_m is the modal radius, and α, γ, and a are the parameters listed in Table I.

TABLE I.

Cloud model	a	α	γ	r_m, μm	r_{eq}, μm	$r_{\rm m}$, μm	N_0, cm^{-3}	w, g/m^3
C1	2.373	6	1	4	6.0	4.7	100	0.0625
C2	$1.0851\cdot10^{-2}$	8	3	4	4.3	4.0	100	0.0301
C3	5.5556	8	3	2	2.2	2.0	100	0.00377
C5	0.5481	4	1	6	10.5	7.5	100	0.297
C7	0.05	3	1	10	20.0	13.3	37	0.689
C8	0.005	3	1	15	30.0	19.9	18.7	1.174
C6	0.0005	2	1	20	49.4	29.1	1.0	0.251

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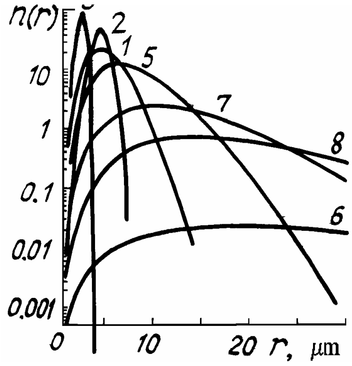

FIG. 1. Cloud droplet size distribution function. Here and in the following figures the number near the curve corresponds to that of the cloud model.

Here r_{eq} and r_m are equivalent and mean radii, N_0 and w are the mean values of droplet concentration and water content, respectively. The cloud models C1, C2, and C3 were taken from Ref. 4 while the C5 and C6 models – from Ref. 9. Since the modal radius of the C5 cloud differed from that of the C6 cloud by more than a factor of 3, the models C7 and C8 were constructed additionally with the modal radii of 10 and 15 μm, respectively. The distribution functions are shown in Fig. 1. Here and in the following figures the numbers near the curves indicate the cloud model.

Now we proceed to the analysis of the optical characteristics of clouds which are known to be determined by the cloud microstructure.

In the visible range, the extinction coefficient ε and r_{eq} are related by the expression[3]

$$\varepsilon = \frac{3}{2}\frac{w}{\rho r_{eq}}, \tag{2}$$

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

$$r_{eq} = \int_0^\infty n(r)\, r^3 dr \Big/ \int_0^\infty n(r)\, r^2 dr\,. \tag{3}$$

It follows from Eq. (2) and Table I that the extinction coefficients for various cloud models differ by more than a factor of two even if they are calculated for the fixed water content (Fig. 2)

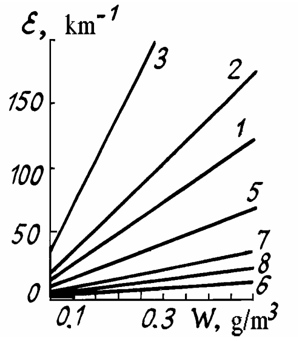

FIG. 2. The dependence of the extinction coefficient ε on the water content w.

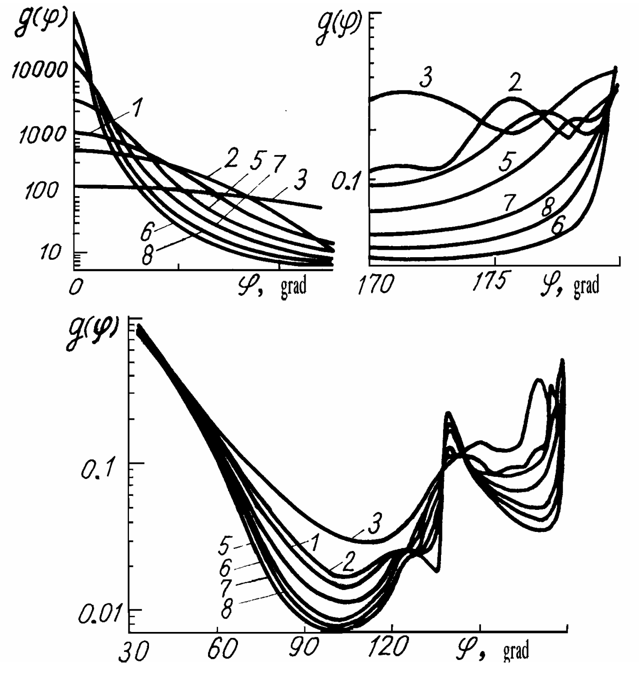

FIG. 3. The scattering phase function.

Also the scattering phase functions being computed at a wavelength of 0.69 μm based on the Mie theory according to the procedure described in Ref. 10 differed substantially. Thus, at zero scattering angle the values of the scattering phase functions can differ approximately by three orders of magnitude (Fig. 3).

MEAN RADIATION FLUXES

The radiative characteristics were calculated based on the direct simulation technique[11] for the statistically uniform and anisotropic model of broken cloud field simulated with the help of the Poisson point processes on the OX and OY axes.[12] The interaction of the radiation with the aerosol gaseous atmosphere and underlying surface was neglected.

The calculations were made for a unitary flux of solar radiation and for the clouds with the mean horizontal size $D = 0.25$ km located with the thickness $H = 0.5$ km. The values of other parameters are given in the figure captions.

The cloud model C1 is most widely used in calculations of the radiative characteristics of broken clouds (see, for example, Refs. 12–14), therefore we will compare the mean fluxes calculated for various cloud models, with the radiative characteristics obtained for the cloud model C1. Note that the dependence of mean fluxes on the solar zenith angle and the optical–geometric parameters of clouds was investigated in detail in Ref. 12.

We denote by $g(\kappa)$ and $\varepsilon(\kappa)$ the scattering phase function and the extinction coefficient of kth cloud model, by $S(\kappa)$, $Q_s(k)$, and $R(\kappa)$ the mean fluxes of unscattered and scattered transmitted and reflected radiation, calculated with the optical characteristics $g(\kappa)$ and $\varepsilon(\kappa)$, and by $\delta S(\kappa)$, $\delta Q_s(\kappa)$, and $\delta R(\kappa)$ the relative differences between the fluxes calculated for the first (C1) and kth cloud model.

When the Sun is at the zenith, we have for the mean flux of unscattered radiation

$$S(k) = 1 - N + N\,e^{-\tau(\kappa)}, \tag{4}$$

where $\tau(k) = \varepsilon(\kappa)H$ is the cloud optical thickness and N is the cloud amount.

It follows from Eq. (4) that $S(\kappa)$ values differ to the maximum extent for $N = 1$ (Fig. 4). For larger solar zenith angles and fixed $N \neq 1$, the fraction of the unscattered radiation having passed through the cloud top and sides ($\sim H\tan\xi$) increases, and therefore $S(\kappa)$ decrease while the maximum of the absolute difference $\Delta S(\kappa)$ is shifted toward smaller N. For fixed parameters of the problem at $\xi = 60°$, $\Delta S(6)$ reaches its maximum at $N \sim 0.4$, and the relative differences $|\delta S(6)|$ are approximately equal to 160% (Fig. 4b). An increase in the water content by a factor of two causes the maximum for $|\delta S(6)|$ fall approximately to 70% (Fig. 4c).

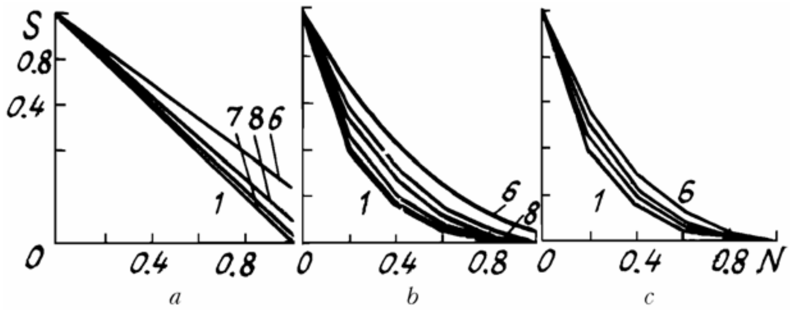

FIG. 4. The mean flux of the unscattered radiation S as a function of the cloud amount N for $w = 0.1$ g/m^3 *at* $\xi = 0°$ *(a) and* 60° *(b); for* $w = 0.1$ g/m^3 *at* $\xi = 60°$ *(c).*

TABLE II.

Cloud model	$\tau = 5$				$\tau = 20$			
	$Q_s(\kappa)$	$\lvert\delta Q_s(\kappa)\rvert$	$R(\kappa)$	$\lvert\delta R(\kappa)\rvert$	$Q_s(\kappa)$	$\lvert\delta Q_s(\kappa)\rvert$	$R(\kappa)$	$\lvert\delta R(\kappa)\rvert$
C6	0.818	7	0.176	25	0.466	20	0.534	12
C1	0.763	–	0.231	–	0.392	–	0.608	–
C3	0.692	9	0.302	30	0.328	16	0.672	10

Now we proceed to the analysis of the fluxes of scattered radiation. Since the differences between the optical parameters of the model C1 and the corresponding parameters of the models C3 and C6 are maximum (Figs. 1, 2, and 3), in what follows we will compare these three cloud models alone.

Let us first of all evaluate the effect of the scattering phase function (at fixed ε) on δQ_s and δR. The calculated results for the continuous cloud cover ($\xi = 0°$) at two optical thicknesses τ are presented in Table II.

It follows from Table II that the relative differences of albedos $|\delta R(3)|$ and $\delta R(6)$ decrease with τ, while for $|\delta Q_s(6)|$ and $\delta Q_s(3)$ the dependence is reversed. For example, according to Table II, as the optical thickness increases by a factor of four, the values of $|\delta R(3)|$ and $\delta R(6)$ decrease approximately by factors of three and two, respectively, while the values of $|\delta Q_s(6)|$ and $\delta Q_s(3)$ increase by the same factors. At a fixed water content the values of δQ_s and δR are determined by the differences not only in the scattering phase function but also in the extinction coefficient. The growth of r_{eq} results in the decrease of the cloud optical thickness, and the elongation of the scattering phase function in the forward direction becomes stronger (Figs. 2 and 3). Since each of these effects results in the increase of Q_s and in the decrease of R, then with an increase of r_{eq} (the water content is fixed), the differences δQ_s and δR of the fluxes of scattered radiation increase.

The dependences of the mean fluxes of scattered radiation Q_s and R on the cloud amount N are shown in Figs. 5 and 6. If the sun is at the zenith then for the fixed parameters of the problem the values of $\delta Q_s(3)$ and $|\delta Q_s(6)|$ increase with N and reach their maxima at $N = 1$, which are equal approximately to 60 and 40%, respectively. The differences in the albedos are practically independent of N and for $N = 1$ $|\delta R(3)| \sim 65\%$, while $\delta R(6) \sim 90\%$ (Fig. 6a). For larger solar zenith angle ξ, the differences $\delta Q_s(3)$ and $|\delta Q_s(6)|$ also increase as water content w and cloud amount N grow, while $|\delta R(3)|$ and

$\delta R(6)$ decrease. For example, for $N = 1$ and $w = 0.1$ g/m^3 at $\xi = 60°$, $\delta Q_s(3) \sim 60\%$ and $|\delta Q_s(6)|$ grows to 115% (Fig. 5*b*), while the values of $|\delta R(3)|$ and $\delta R(6)$ fall approximately to 35 and 70%, respectively (Fig. 6*b*). The growth of the water content by a factor of two for $N = 1$ at $\xi = 60°$ causes the differences $|\delta Q_s(6)|$ reach 210% (Fig. 5*c*), while $\delta R(6)$ falls to 60% (Fig. 6*c*). Note that the radiative characteristics $S(3)$, $Q_s(3)$, and $R(3)$ were not calculated for the water content $\omega = 0.2$ g/m^3, since in this case the extinction coefficient $\varepsilon(3)$ is equal to 150 km^{-1}, i.e., the value which has never occured in nature.[2]

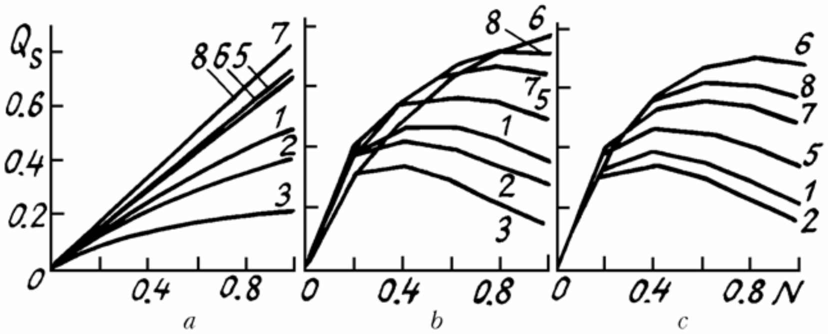

FIG. 5. The effect of the cloud amount N on the mean flux of the scattered transmitted radiation Q_s for $\omega = 0.1$ g/m^3 *at* $\xi = 0°$ *(a) and* $\xi = 60°$ *(b); for* $\omega = 0.2$ g/m^3 *at* $\xi = 60°$ *(c).*

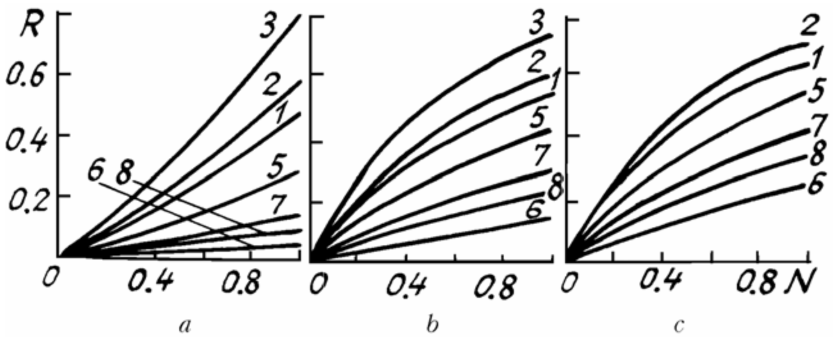

FIG. 6. The dependence of the mean flux of the scattered reflected radiation R on the cloud amount N for $\omega = 0.1$ g/m^3 *at* $\xi = 0°$ *(a) and* $\xi = 60°$ *(b); for* $\omega = 0.1$ g/m^3 *at* $\xi = 60°$ *(c).*

We denote the mean fluxes of scattered transmitted and reflected radiation of stratus clouds calculated at fixed values of optical characteristics $g(\kappa)$ and $\varepsilon(\kappa)$ by $Q'_s(\kappa)$ and $R'(\kappa)$. The dependences of $Q'_s(\kappa)$ and $R'(\kappa)$ on the cloud amount take the forms

$$Q'_s(\kappa) = NQ^*_s(\kappa)\ , \tag{5}$$

$$R'(\kappa) = NR^*(\kappa)\ , \tag{6}$$

where $Q^*_s(\kappa)$ and $R^*(\kappa)$ are the corresponding radiative characteristics calculated for the continuous cloud cover.

It follows from Eqs. (5) and (6) that $\delta Q'_s(\kappa)$ and $\delta R'(\kappa)$ are independent of N and coincide with $\delta Q_s(\kappa)$ and $\delta R(\kappa)$ calculated for $N = 1$. Since for $N = 1$ $0.1 \le \omega \le 0.2$, $0° \le \xi \le 60°$, and $H = 0.5$ km, the differences $|\delta Q_s(\kappa)|$ reach their maximum and $|\delta R(k)|$ – their minimum, then for $N \ne 1$ and for the fixed parameters of the problem the inequalities $|\delta Q'_s(\kappa)| > |\delta Q_s(\kappa)|$ and $|\delta R'(\kappa)| < |\delta R(\kappa)|$ hold.

CONCLUSION

By analyzing the calculated results one can draw the following conclusions.

1. There is a strong dependence of radiative characteristics of the cloudy atmosphere on the microphysical parameters of clouds. The ignorance of the microstructure of clouds can result in the substantial differences in the radiation fluxes which for the transmitted scattered radiation can exceed 200%, while for the albedo they are approximately equal to 100%.

2. Variations of the microstructure of stratus clouds result in greater variations in the flux of scattered transmitted radiation than the variations of the microphysical parameters of cumulus clouds. For the albedo the dependence is reversed.

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