Albedo and Reflected Radiance of Horizontally Inhomogeneous Clouds

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ABSTRACT

The Monte Carlo method has been applied to the transfer of solar radiation through clouds with horizontal inhomogeneities which are assumed to consist of horizontally periodic striations. At a wavelength of $\lambda=0.55$ μm the cloud albedo and reflected radiance are calculated as functions of cloud drop size distribution, optical thickness, solar geometry and type of cloud striations. The resulting cloud albedo is shown to be lower for striated clouds than for a plane parallel cloud with the same mean optical thickness. The largest differences of about 20% occur for a striated cloud with deep striations when the sun is in the zenith. A change in the cloud drop size distribution has nearly the same influence on the albedo of striated clouds as a change in the type of striations, the optical thickness remaining unchanged. A comparable influence results for the radiance reflected from striated clouds, although in this case it depends upon solar geometry and angle of the emerging radiance. It is shown that the radiance emerging from striated clouds can reach even larger values than that reflected by a plane parallel cloud with a thickness equal to the largest thickness of the striated cloud. This effect is due to the backscattering from the vertical walls of the cloud columns occuring at intermediate sun elevation angles in the antisolar direction. On the other hand, the reflected radiance of striated clouds is shown to be reduced compared to that of a plane parallel cloud by the effect of shadows. The magnitude of this effect is mainly determined by the optical thickness.

1. Introduction

The accurate determination of the radiation balance of the earth-atmosphere system requires a detailed knowledge of the radiation reflected and emitted by clouds. All efforts up to now to include the radiative effects of clouds in the determination of the albedo of the earth-atmosphere system have been limited to the effects of plane parallel cloud layers. Real clouds, however, are often formed by convection and show irregular surfaces or occur in discrete cloud cells. Often the vertical and horizontal dimensions of the clouds involved are of the same size, ranging from isolated cumulus clouds to large cloud clusters, thus affecting the radiation balance in a quite different order.

With regard to the transfer of radiation through clouds with horizontal inhomogeneities, only a limited number of mainly theoretical investigations are reported. One of the first papers centering on this problem has been published by Weinman and Swarztrauber (1968). They calculated the albedo of a stratified cloud with a sinusoidal variation of the optical thickness in one horizontal direction. In order to reduce computational difficulties the authors had to make several simplifying assumptions one of which was the approximation of symmetrical scattering of the cloud droplets. Compared to a horizontally homogeneous cloud they got a lower albedo for a deeply striated cloud. Because of the assumption of symmetrical scattering these results cannot be representative for the effects of real cloud droplets which show strong forward scattering. The investigation by Van Blerkom (1971) concentrated on the calculation of the radiance reflected by clouds with periodic inhomogeneities in one horizontal direction. The Monte Carlo method was employed for the calculations assuming isotropic scattering of the cloud droplets. The reflected radiances were shown to differ significantly from those determined under the assumption of a plane parallel cloud geometry. Based on the same computational method is the analysis of scattering of visible radiation by individual cubic clouds presented in the paper of McKee and Cox (1974). These authors used an anisotropic scattering function, thus going one step further in modeling realistic clouds. They obtained drastic differences in the irradiance fields of finite-sized clouds compared to plane parallel clouds. However, this study does not include radiative interaction between a field of separated cubic clouds.

The purpose of this paper is to analyze the effects of horizontally inhomogeneous clouds on the reflected radiation field by using anisotropic scattering func-

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tions for the cloud droplets and by considering the radiative interaction of all parts of the assumed cloud model. The calculations are evaluated by employing the Monte Carlo method and the cloud geometry first introduced by Van Blerkom. It is this model which accurately considers the interaction of all periods of the cloud striations and shows a structure which may arise from convection. Contrary to the papers mentioned above, two different anisotropic scattering functions have been used in order to determine the radiative effects due to variations in the cloud drop size distribution and to compare these effects with those which arise from variations in the horizontal inhomogeneities of the cloud. Both scattering functions are based on aircraft measurements of cloud drop size distributions in stratus clouds. The results are presented as functions of solar geometry, optical thickness and type of striation. All calculations are compared to a plane parallel cloud with an optical thickness equal to the optical thickness of the striated clouds averaged over the horizontal period of the striations. This plane parallel cloud is referred to in the following as the cloud with the same mean optical thickness compared to striated clouds.

2. Computation method and tests

The author believes that the Monte Carlo method is best suited for radiative transfer calculations in clouds with arbitrary shapes. The application of the Monte Carlo method for solving radiative transfer problems has been described in detail by Collins and Wells (1965) and by House and Avery (1969). According to this method radiative transfer calculations are mainly a computer simulation of the radiative transfer processes which are based upon the physical laws of interaction between photons and a prescribed medium. After first introducing these basic physical laws into the computer as probability functions, a system of coordinates and boundaries are defined and photons are then released as a computer experiment. The photons are traced as they diffuse through the medium following the physical interaction laws, which are sampled by the selection of numbers from a quasi-random sequence. The photons are followed until they escape from the medium, with desired quantities such as the direction and the state of polarization of the photon being recorded. Many other parameters can be easily obtained, such as the distribution of the internal radiation field, the mean number of collisions undergone by a photon as well as the reflection, transmission and absorption of the medium.

The following computations of radiative transfer problems by Monte Carlo analysis are governed by the simulation of only two processes, the distance between two collisions of the photon and the change

TABLE 1. Cloud albedo calculated with the Monte Carlo method compared to calculations with the matrix operator method for a Deirmendian cloud C1 drop size distribution at a wavelength of 0.55 μm. The results are compared as function of the optical thickness and the cosine of the zenith angle of the sun.

Optical thickness	Cosine of the sun zenith angle	Cloud albedo: Monte Carlo method	Cloud albedo: Matrix operator method
4	−0.15	0.644	0.646
	−0.95	0.203	0.201
16	−0.15	0.814	0.816
	−0.95	0.555	0.556

in the photon's direction after the scattering by a cloud droplet. Absorption by cloud droplets is not considered in the computations. Using numbers from a random sequence the sampling of the photon's path length distribution is determined by the fundamental equation

$$L = -\Lambda_0 \ln(1-\mathrm{RN}), \tag{1}$$

where L is the distance between successive collisions of the photon, Λ_0 the photon mean free path and RN a random number uniformly distributed between 0 and 1. Whenever RN appears in the following it will have the same meaning. Assuming no absorption by cloud droplets nor by aerosols or gases in the path between two collisions, the photon is advanced by the path length L to undergo scattering by the cloud droplets. It is now necessary to calculate a new direction of the photon following a given scattering probability distribution function. As can be shown this is uniquely done by choosing an random number RN and solving the equation

$$2\pi \int_{180^\circ}^{\theta} f(\theta) d(\cos\theta) = \mathrm{RN} \tag{2}$$

for the upper limit of integration, which is represented by the scattering angle θ. This is the angle between the photon's direction before the collision and the direction after the collision. The angular distribution of the scattered radiation is determined by the single-scattering phase function $f(\theta)$. When integrated over the sphere, $f(\theta)$ is normalized to

$$\int_{0^\circ}^{360^\circ} \int_{0^\circ}^{180^\circ} f(\theta) \sin\theta d\theta d\varphi = 1. \tag{3}$$

The normalized phase function $f(\theta)$ is independent of the azimuthal angle of scattering φ, which is needed to describe uniquely the direction after a collision. Therefore φ will be uniformly distributed in the angular interval between 0° and 360° and sampled

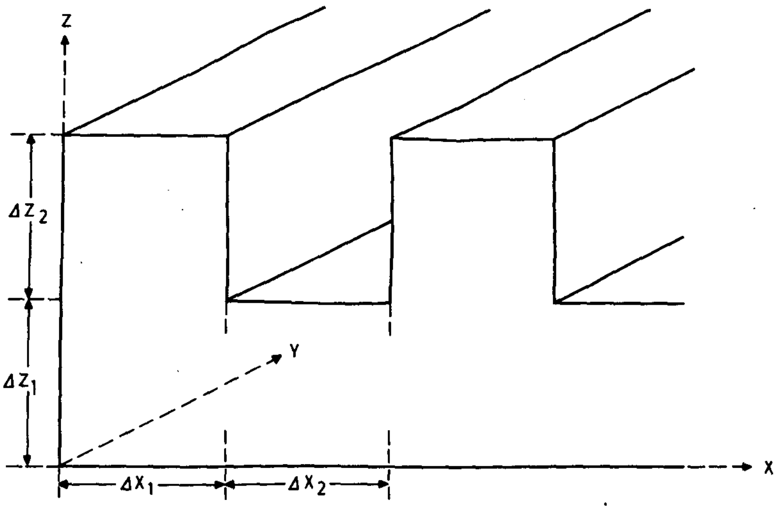


FIG. 1. Cloud model.

by the equation

$$\varphi = 2\pi RN. \tag{4}$$

For realistic cloud drop size distributions the normalized Mie scattering function has a strong forward peak and is usually not given in an analytic form. Therefore, when calculating the scattering angle θ according to Eq. (2) we have to use $f(\theta)$ as a tabulated function. Near the strong forward peak of the scattering function a very small interval tabulation has to be chosen. In our calculations we use steps of $\Delta\theta = 0.05°$ near the forward peak.

Each program that uses the Monte Carlo method must be tested by comparing the results of the whole program to known results. This has been done first by calculating the reflected radiance of an atmosphere with Rayleigh scattering and comparing the results to those of Coulson *et al.* (1960). The reflected radiance is obtained from tabulation of photons which enter detectors positioned at various angles. The radiance is given in the following in relative units normalized to a parallel incident flux of photons of unity falling on a surface perpendicular to the incident beam. The number of photons leaving the atmosphere or the cloud with a specific direction is related to the radiance by

$$I(\mu,\Phi) = \frac{\mu_0 N(\mu,\Phi)}{\mu \Delta\Omega\, N_0}, \tag{5}$$

where $N(\mu,\Phi)$ is the number of photons emerging in the direction μ, Φ (μ = cosine of the zenith angle, Φ = azimuth angle), $\Delta\Omega = \Delta\mu\Delta\Phi$ is the solid angle of each photon collector, N_0 is the number of photons entering the medium and μ_0 is the cosine of the zenith angle of the incident beam. The results of our comparison are shown in Fig. 5. For these and the following test calculations 20 000 photon histories have been traced. As will be shown in Fig. 5 the accuracy of the results decreases going to radiances emerging near the horizon because only few photons go into this direction. A second test result was obtained by calculating the albedo of a plane parallel cloud using a highly anisotropic scattering function based on the drop size distribution denoted by Deirmendjian (1969) as model cloud C1. The cloud albedo is defined as the fraction of the incident light reflected from the cloud. The Monte Carlo result is compared to calculations performed with the matrix operator method following the procedure of Plass (1973). The statistical fluctuation of the Monte Carlo result for the cloud albedo is estimated to be 1–2%. As can be seen from Table 1 the agreement between the results of the two methods is within the range of the statistical fluctuation of the Monte Carlo method and therefore quite satisfactory.

3. Cloud model

The assumed cloud geometry is shown in Fig. 1. The cloud surface is characterized by a regular pattern of striations running from $y = -\infty$ to $y = +\infty$. The length of one period of striations is $\Delta x_1 + \Delta x_2$, while the largest geometrical thickness of the striated cloud is assumed to be $\Delta z_1 + \Delta z_2 = 1$ km. The calculations have been performed for three periodic lengths of the striations: 0.5 km, 1 km and 2 km. No scattering, absorbing or reflecting material is assumed to be situated above and below the cloud boundaries. Because of the structural regularity, the transfer of radiation through the whole cloud can be determined by tracing photons through only one period of the striations. A photon which for instance strikes the boundary plane $x = \Delta x_1 + \Delta x_2$ is replaced by a photon entering the same region at $x = 0$, the direction of the photon remaining unchanged. As is illustrated in

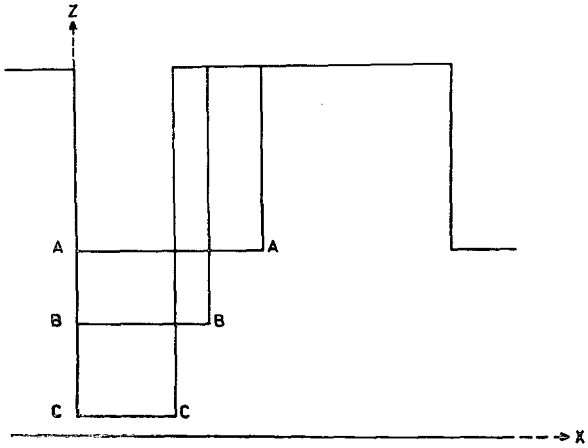


FIG. 2. Striated clouds with different column heights and widths but constant mean optical thickness equal to the optical thickness of a plane parallel cloud of thickness $\Delta z=0.75$ km (cloud type A: $\Delta x_1=0.5$ km, $\Delta x_2=0.5$ km, $\Delta z_1=0.5$ km, $\Delta z_2=0.5$ km; cloud type B: $\Delta x_1=0.357$ km, $\Delta x_2=0.643$ km, $\Delta z_1=0.3$ km, $\Delta z_2=0.7$ km; cloud type C: $\Delta x_1=0.263$ km, $\Delta x_2=0.737$ km, $\Delta z_1=0.05$ km, $\Delta z_2=0.95$ km). See also Fig. 1.

Fig. 2 three types of striated clouds are considered in the following: A, B and C. When averaged over one period of the striations, all these cloud types have the same mean optical thickness which is equal to three-fourths of the optical thickness of a 1 km thick plane parallel cloud. The sun is assumed to illuminate the striated cloud parallel to the (x,z) plane. The Monte Carlo computations are initiated by having entered a photon at some point x in the plane $z=\Delta z_1+\Delta z_2$ given by $x=\mathrm{RN}(\Delta x_1+\Delta x_2)$. By this procedure and with a given zenith angle θ_0 and azimuth angle Φ_0 of the photon, the point of entrance is uniquely determined. Thus the sum of all entering photons defines a monodirectional illumination of the striated cloud.

The drop size distributions chosen for this calculation are those which have been measured in stratus clouds by Diem (1942) and by Pedersen and Todsen (1960). These distributions are quite different, both in the absolute number of droplets (cm^{-3}) and in the radius at which the distributions have their maximum (Fig. 3). Both distributions have been normalized to a liquid water content of 0.1 g m^{-3}. All the following calculations refer to a wavelength of 0.55 μm. For water drops a real index of refraction of 1.33 was assumed. By applying Mie theory for the scattering on water droplets we obtained the scattering functions for both size distributions as shown in Fig. 4. The size distribution of Diem has more large droplets than the distribution of Pedersen and Todsen which results in an increased forward scattering. Effects of polarization on the scattering by water droplets are not considered.

In order to get good statistical estimates of the quantities of interest—the cloud albedo and the reflected radiance—it is necessary to process a large number of photons. The accuracy of a Monte Carlo simulation is proportional to the square root of the number of photons counted and can be estimated by repeating the calculation of the quantity of interest. The following results for striated clouds are based on a tracing of 50 000 photons, those for plane parallel clouds on a tracing of 20 000 photons. The average number of collisions sampled in our calculations varies between about 480 000 and 1 550 000, depending strongly on the optical thickness of the cloud. Compared to this influence there is only a small influence of the periodic length of the striations and the type

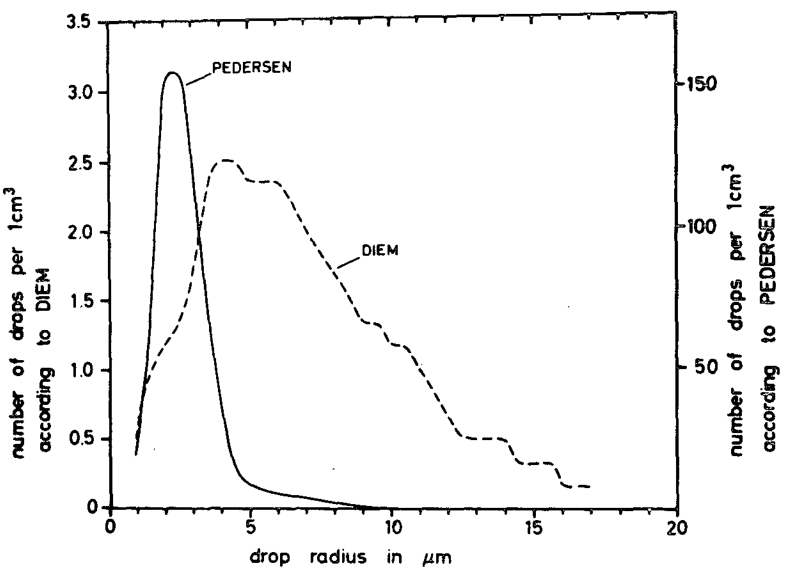


FIG. 3. Drop size distributions in stratus clouds according to Diem (1940) and Pedersen and Todsen (1960) normalized to a liquid water content of 0.1 g cm^{-3}.

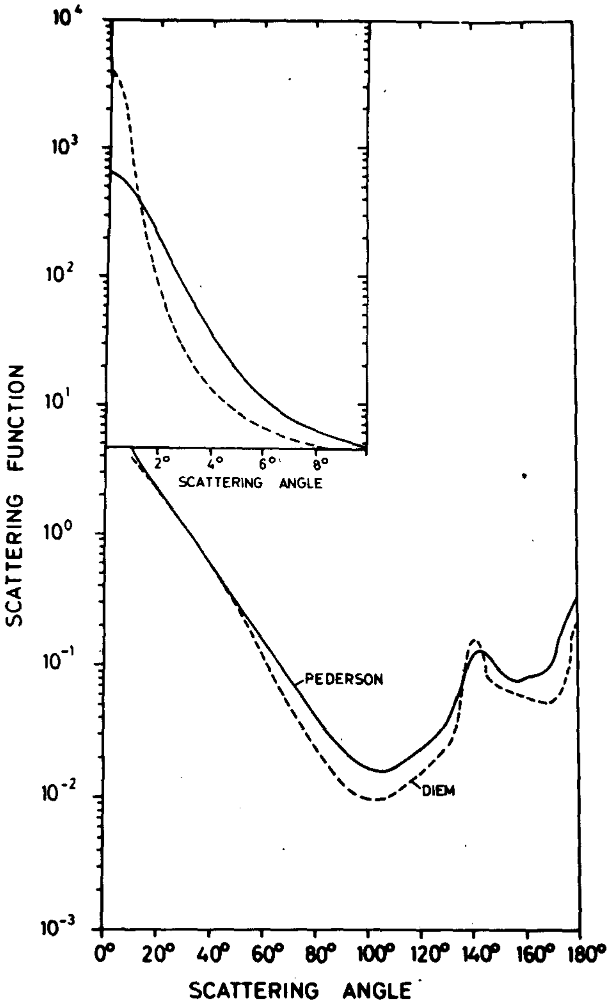


FIG. 4. Angular scattering function for Mie scattering as function of the scattering angle for the cloud drop size distributions shown in Fig. 3 at a wavelength of 0.55 μm.

of striations on the average number of collisions. The resulting accuracy of the cloud albedo is estimated to be about $\pm$0.8–2%, while the accuracy of the presented cloud radiances varies between $\pm$5% and $\pm$12%, depending on the optical thickness of the cloud and the emerging angle of the reflected radiance. Radiances at large zenith angles will be, in general, less accurate than those emerging at smaller zenith angles because only a few photons leave clouds under large zenith angles.

4. Results and discussion

The results for the albedo of striated and plane parallel clouds are given in Tables 2–4. For striated clouds the albedo is averaged over the horizontal periodic length of the striations. The results of Table 2 show that the striated clouds with the sun at the zenith always have lower albedos than the corresponding plane parallel cloud with the same mean optical

TABLE 2. Albedo of striated clouds with different column heights and widths but constant mean optical thickness (period of striations = 1 km, Pedersen and Todsen droplet spectrum, σ_E = 20.5 km^{-1}).

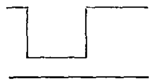
	Cloud albedo			
Sun zenith angle	Striated cloud type A	Striated cloud type B	Striated cloud type C	Plane parallel cloud ΔZ = 0.75 km
$\mu_0 = -1.0$	0.519	0.488	0.445	0.562
$\mu_0 = -0.7$	0.646	0.647	0.637	0.646
Cloud type				

thickness (cloud with Δz = 0.75 km). The differences between the striated clouds and the plane parallel cloud increase with decreasing zenith angle of the sun and come up to 20% in the case of the striated cloud of type C when the sun is in the zenith. Compared to all other striated cloud types the type C has the lowest albedo. The reason for this is that the cloud of type C has the deepest striations. When the sun is in the zenith these will act as a light trap. Photons going downward easily penetrate the remaining bottom layer of the cloud and are lost for reflection. Photons going upward from the bottom of the striations must move within a very narrow angular range so as to be able to leave the striations without further collisions in the columns. Since both this angular range as well as the thickness of the remaining cloud bottom layer increase for the clouds of type A and B the albedo of these cloud types will be higher than for a cloud of type C. When the sun elevation is lower the role of the bottom layer of the striations is weakened because the direct beam of the sun strikes only the upper part of the cloud columns. The albedo of the striated clouds now depends on two effects. On the one hand the reflected radiation decreases because

TABLE 3. Albedo of striated clouds (type A) as function of droplet spectrum and optical thickness (period of striations = 1 km).

	Cloud albedo	
Sun zenith angle	Droplet spectrum Pedersen and Todsen (1960)	Droplet spectrum Diem (1942)
	σ_E = 7.8 km^{-1}	
$\mu_0 = -1.0$	0.281	0.236
$\mu_0 = -0.2$	0.671	0.649
	σ_E = 20.5 km^{-1}	
$\mu_0 = -1.0$	0.519	0.471
$\mu_0 = -0.2$	0.808	0.790

Table 4. Albedo of striated clouds (type A) as function of the periodic length of striations (Pedersen and Todsen droplet spectrum, $\sigma_E=20.5\ \text{km}^{-1}$)

Sun zenith angle	Cloud albedo Period of striations $\Delta x=0.5$ km	 Period of striations $\Delta x=2$ km
$\mu_0=-1.0$	0.502	0.535
Cloud type		

large parts of the striated clouds are shadowed, while on the other hand, there is an increased backscattering of the illuminated side walls of the cloud columns in the antisolar direction. The backscattered radiation from the side walls can be larger than the radiation reflected by a plane parallel cloud in the antisolar direction as will be shown later. This effect can compensate the effect of the shadowed parts as is shown in Table 2. For $\mu_0=-0.7$ the cloud of type A has the same albedo as the plane parallel cloud with the same mean optical thickness. The striated cloud of type C has a slightly lower albedo because the striations are now smaller and deeper. There is a larger probability that photons which are backscattered from the illuminated side walls of the columns will reach the bottom of the striations by multiple scattering. If this occurs, these photons will penetrate the thin bottom layer and be lost for reflection.

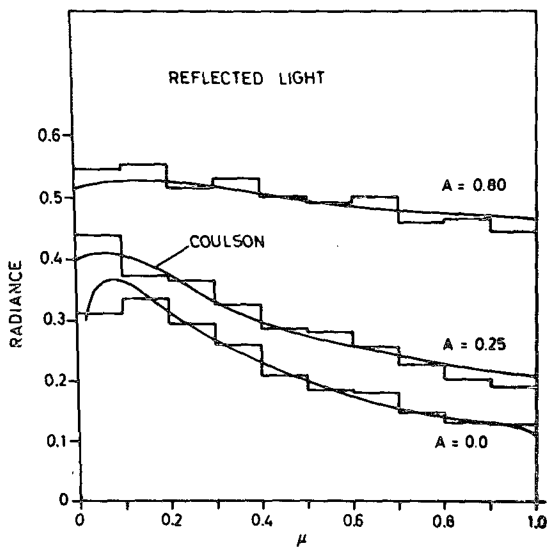


Fig. 5. Reflected radiance for a Rayleigh scattering atmosphere of optical thickness $\tau=0.5$ as function of the cosine of the zenith angle μ and the surface albedo A for a cosine of the zenith angle of the sun $\mu_0=-0.6$. The continuous curve refers to the results given in the tables of Coulson *et al.* (1960) averaged over all azimuthal angles. 20 000 photon histories have been traced.

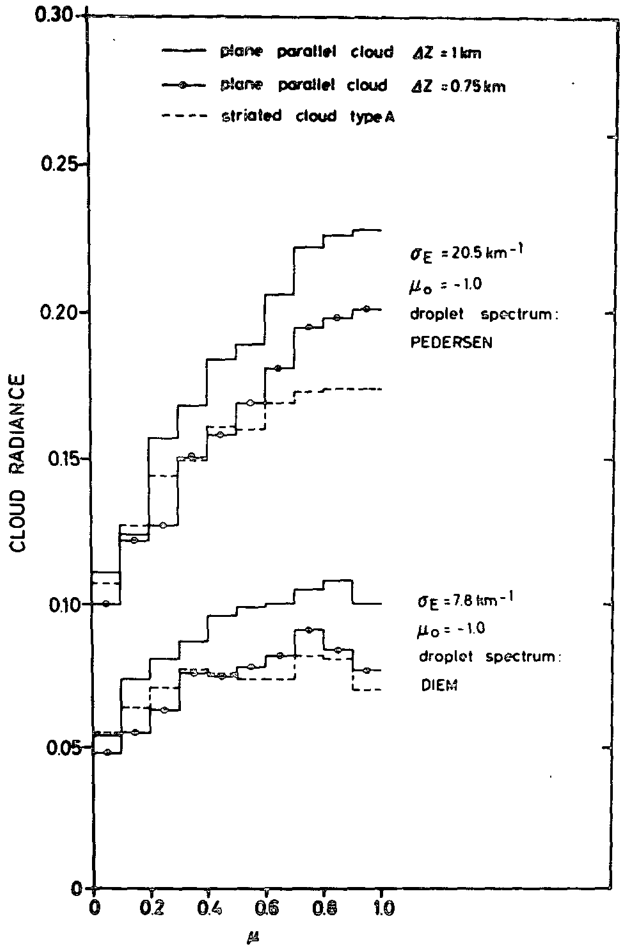


Fig. 6. Reflected radiance of striated and plane parallel clouds as function of the cosine of the zenith angle for a cosine of the sun zenith angle of $\mu_0=-1.0$. The calculations are done for two optical thicknesses (upper and lower part) given in terms of the extinction coefficient σ_E, which is based on the drop size distributions of Fig. 3. The periodic length of the cloud striations is 1 km for the calculations of Figs. 6–9.

The radiative effects of a variation in the cloud drop size distribution are demonstrated in Table 3. Considering only a striated cloud of type A the calculations have been carried out for two optical thicknesses which are given in Table 3 in terms of the extinction coefficient σ_E. The cloud with the Diem drop size distribution always shows a lower albedo due to the enhanced forward scattering compared to the Pedersen and Todsen distribution. The differences decrease with increasing optical thickness and increasing zenith angle to the sun. With increasing optical thickness we have more scattering events and the differences between the two scattering functions are smoothed. On the other hand, when the sun illuminates the cloud at large zenith angles the slant optical thickness is increased, thus affecting the scattering of the photons in the same way. If we look at the cloud with an extinction coefficient of $\sigma_E=20.5$

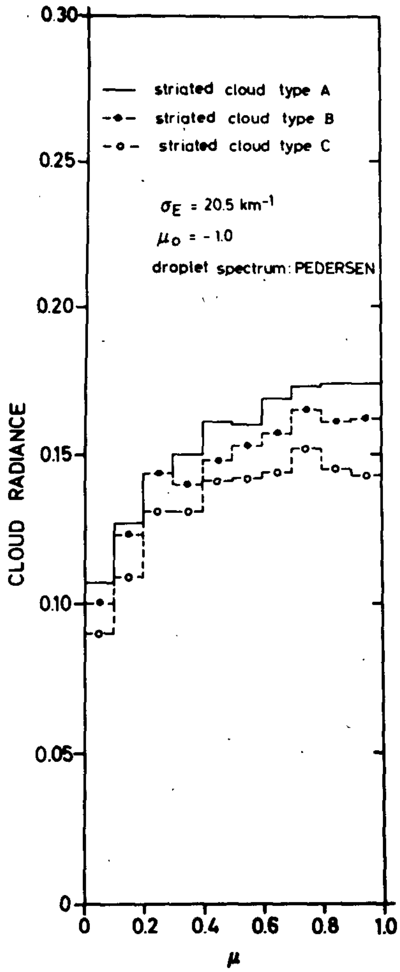


FIG. 7. Reflected radiance of striated clouds for $\mu = -1.0$ as a function of the type of striation according to Fig. 2.

km^{-1} and a zenith angle of the sun of $\mu_0 = -1.0$, we obtain differences in the cloud albedo of the same order by changing the scattering function from that of Pedersen and Todsen to that of Diem as if we had changed the cloud surface structure from type A to type B in Table 2.

The question may arise as to how the cloud albedo changes with the periodic length of the striations. The results are shown in Table 4 for two periodic lengths of the striations and the sun in the zenith. According to these results variations in the periodic length of the striations have a much smaller influence on the cloud albedo than variations in the cloud surface structure. The main reason for this is that the height of the bottom of the striations in both cases has not been changed. Thus, for a periodic length of 0.5 km, even if the angular range for photons going upward without further collisions is reduced compared to a cloud with a periodic length of 2 km, photons have a chance to contribute to the reflection because the columns turn out to become optically thinner when the periodic length of the striations decreases. On the other hand, the fraction of photons reflected back by the upper part of the columns remains nearly constant because no change of the optical thickness in the direction of the illuminating beam occurs when the periodic length of the striations is changed. Therefore, further decrease of the periodic length of the striations will not change the albedo significantly. However, further increase of the periodic length of the striations will approach the value of the albedo to that of a plane parallel cloud with the same mean optical thickness.

Nearly all radiation measurements from satellites are basically radiance measurements. It is therefore important to know how cloud radiance measurements are affected by horizontally inhomogeneous clouds. The largest differences between the radiance reflected by a striated cloud and that reflected by a plane parallel cloud with the same mean optical thickness occur when the sun is in the zenith and we look at the radiance emerging near the zenith. This is shown

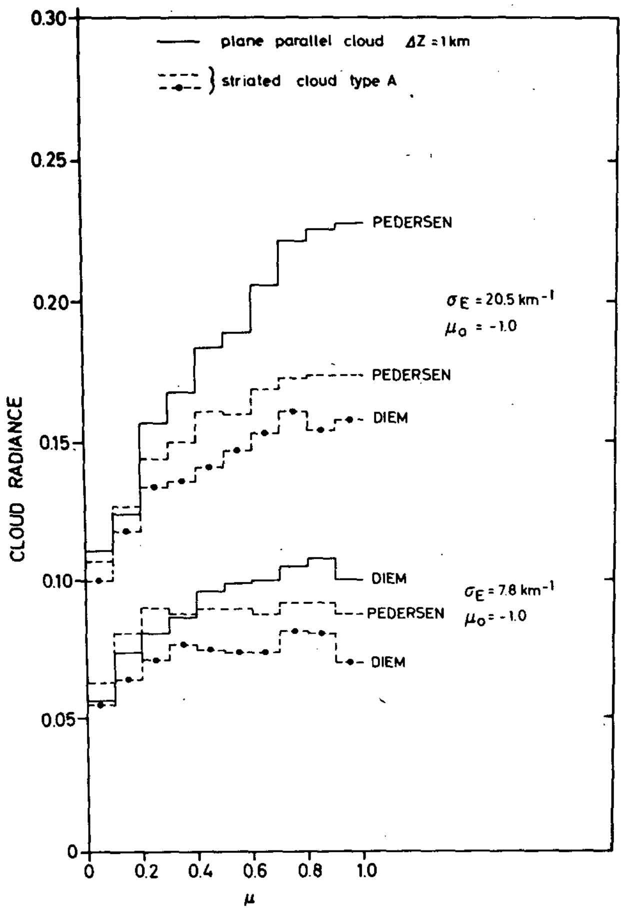


FIG. 8. Reflected radiance of striated and plane parallel clouds for $\mu_0 = -1.0$ as a function of the drop size distribution, the optical thickness remaining unchanged. The calculations are done for two optical thicknesses (upper and lower part).

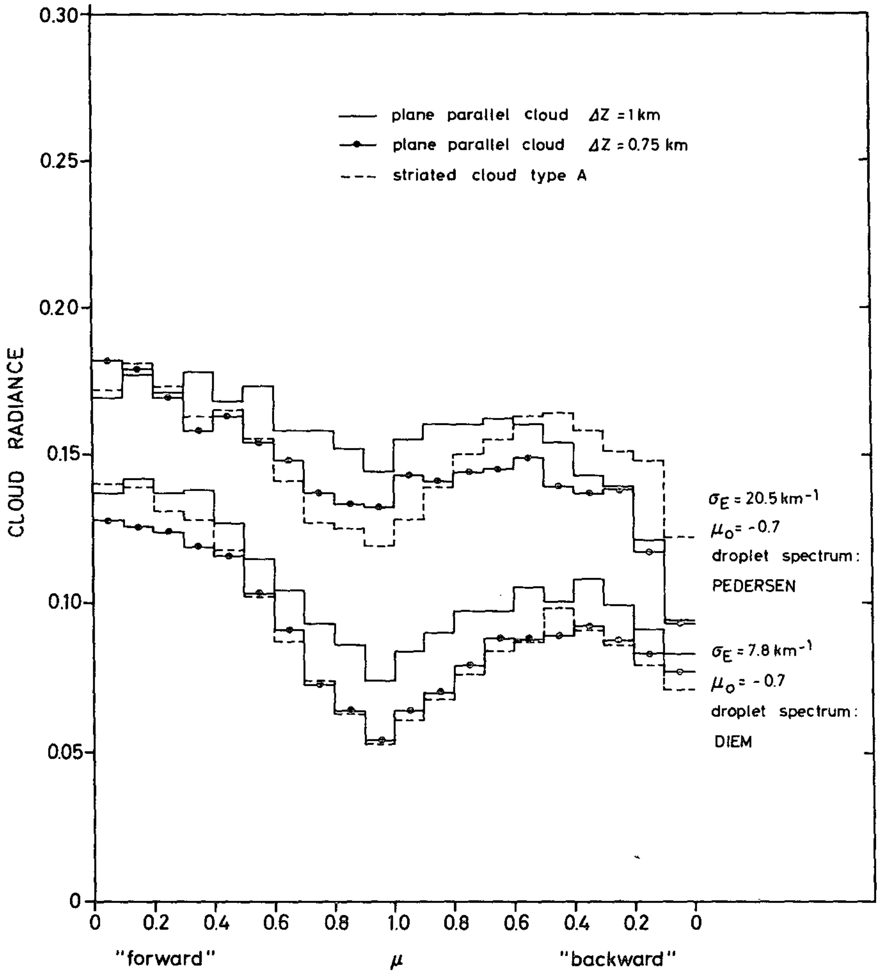


Fig. 9. Reflected radiance of striated and plane parallel clouds for $\mu_0 = -0.7$ and two optical thicknesses (upper and lower part).

in Fig. 6. All radiances are averaged over the periodic length of the striations and over the azimuthal range of $270° \leqslant \Phi \leqslant 90°$ as well as over the range of $90° < \Phi < 270°$, thus separating photons going into the "forward" and "backward" directions ($\Phi = 0°$, positive x axis). Both radiances are the same when the cloud is illuminated by the sun in the zenith. Therefore only one part of the radiance is shown in Fig. 6 in this case. As is illustrated in Fig. 6 the reflected radiances fall off to a minimum at the horizon where the effect of the striations nearly disappears. The reflected radiance of the striated cloud can be well represented by that of a plane parallel cloud with the same mean optical thickness in the case of a low optical thickness (lower part of Fig. 6). However, with increasing optical thickness this approximation can be applied only for radiances emerging near the horizon (upper part of Fig. 6). The radiances resulting from a change in the cloud surface structure are shown in Fig. 7. The radiances reflected by a cloud with striations of type C are always lower than those reflected by clouds of types A and B. This is due to the deepness of the striations of type C which causes many photons to be lost for reflection. A change in the cloud drop size distribution accounts for differences in the reflected radiance which are of the same order as if the cloud surface structure were changed. This is indicated by comparing the results for the radiance near the zenith of Fig. 7 with the corresponding results of the upper part of Fig. 8.

The radiance reflected by a striated cloud can even become larger than that reflected by a plane parallel cloud with the full thickness of $\Delta z = 1$ km as is shown by Fig. 9 for a cosine of the sun zenith angle of $\mu_0 = -0.7$. The reason for this is the strong backscattering from the vertical walls of the columns illuminated by the sun. Thus these walls act as a mirror. The magnitude of this mirror effect decreases with decreasing optical thickness which can be seen in the lower part of Fig. 9. The effect of the shadowed parts of a striated cloud on the reflected radiance is shown by looking at the radiance emerging near the zenith and at lower elevation angles in the "forward" direction. The shadow-effect decreases with decreasing optical thickness (compare the upper and lower parts of Fig. 9). This is due to the fact that clouds with a low optical thickness have no shadowed parts as can be seen by looking at an inhomogeneous surface of a fog layer. The results of Fig. 9 also demonstrate that for lower sun elevation angles the reflected radiance of striated clouds with low optical thickness is approximated quite well by the reflected radiance of the corresponding plane parallel cloud.

5. Conclusions

The main results of this investigation can be summarized as follows: The comparison between the radiative effects of clouds with periodic striations in one horizontal direction and plane parallel clouds of the same mean optical thickness indicates that the albedo of striated clouds is always lower. The plane parallel cloud with the same mean optical thickness is only a good approximation for the cloud albedo of striated clouds when the striations are not too deep and when the sun illuminates the cloud at low angles. A change in the cloud drop size distribution, the optical thickness remaining unchanged, can affect the cloud albedo by the same magnitude as a change in the type of the cloud striations. The cloud albedo of striated clouds is shown to be nearly independent of the periodic length of the striations.

The reflected radiance of striated clouds is approximated quite well by that of a plane parallel cloud with the same mean optical thickness only in the case of a low optical thickness. For clouds with larger optical thicknesses this approximation is suitable only for the radiance emerging near the horizon. The effects of a change in the cloud drop size distribution are of the same order as those of a variation of the type of the cloud striations when the sun is incident near the zenith and the radiance emerging near the zenith is considered. The radiance reflected by striated clouds can even reach a larger value than that reflected by a plane parallel cloud which has a thickness equal to the largest thickness of the striated clouds. This occurs in the antisolar direction when the sun is incident at intermediate elevation angles. The magnitude of this effect decreases with decreasing optical thickness.

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