SOME PECULIARITIES IN THE RADIATION TRANSFER THROUGH A CLOUDY ATMOSPHERE

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Received August 1, 1997

Some peculiarities of the optical radiation propagation through clouds are treated in this paper. The clouds of the highest symmetry are shown to be the main contributors into the albedo of a cloudy atmosphere. The effect of anomalous transmission of broken clouds for radiation is a consequence of both the clearing-up of the disperse medium layer at its breaking and of a sharp fall off of the absorption caused by the increase of the cloud quantity followed by a decrease in the optical size of an isolated cloud. In a stratified cloudiness the decisive influence on the transmittance and reflectance is exerted by the upper layer of the clouds.

Cloud formations strongly affect the radiation budget of the atmosphere. One can assume that the problem of calculating the radiation budget in the case of continuous and broken cloudiness is solved,[1–4] but some difficulties appear in the physical interpretation of the experimental data on propagation of radiation through a cloud system. As an example, one can note such problems as "anomalous absorption" and ambiguity in the results obtained from ground-based and space-based sounding of cloudiness. Obviously, these problems are the consequence of an incorrect account for the structure, geometric, and optical parameters of cloudiness. Since the problem has many parameters, its solution in the general case, often leads to ambiguous results caused by the difficulty of taking into account simultaneous effect of different parameters on the radiative budget, so the study of all aspects is necessary for a more comprehensive analysis of the problem.

In this paper we state the general physical features of the radiation transfer in broken cloudiness.

It is known that the development of cloud formations is accompanied by the following processes: an increase in the geometric and optical size of some clouds and the change of their shape; joining up of separate clouds and formation of cloud fields; change of microphysical and optical properties of cloudiness, such as the scattering phase function and the single scattering albedo Λ; and the change of the cloud layer structure.

Let us consider the effect of each process on the radiation budget separately. Growth of the geometric size of clouds is usually accompanied by an increase in their optical size, the microphysical parameters can remain constant. The increase of the optical volume of cloud affect the components of its radiative budget. One should expect these components to depend not only on the optical volume of the scattering medium, but also on its shape. Let us use the cloud model that represents it as a parallelepiped of the optical length τ_x, width τ_y, and height τ_z. Let it be illuminated uniformly with a collimated radiation flux directed along the normal to the yz plane in a Cartesian coordinate system. The scattering phase function is characterized by the mean cosine of the scattering angle g. We studied the effect of the size and shape of the optical volume on the values of the transmittance T and reflection R of the cloud with the scattering phase function C1. We varied the medium shape by changing the relationship between τ_x and $\tau_y = \tau_z$. The optical volume V defined for the parallelepiped as a product $\tau_x \times \tau_y \times \tau_z$, was used as a general characteristic of clouds of different size and shape. The dynamical cloud model was based on the following ideas: an increase in the vertical optical density of a cloud is usually accompanied by an increase in the horizontal one, the latter increases essentially more quickly than the vertical one. The results of investigations are shown in Fig. 1. The data obtained show that the values T and R strongly depend on the shape of the scattering volume. As known, it is the optical thickness of a cloud that principally affects its transmittance, while the dependence of reflection on the ratio τ_x/τ_y characterizing the volume shape has the shape of a curve with maximum (Fig. 1*b*). Let us note that the maximum reflection is observed for the medium, the shape of which has the greatest degree of symmetry (a cube in our case).

Let us now consider the effect of clearing-up of the disperse medium layer when breaking it.[5] Let us understand by the clearing-up effect the following: an increase of T when breaking the medium of a constant optical length to N pieces of the same length and correspondingly keeping the same conditions of illumination and observation. Since the purpose of this paper is to study the physical features in their pure

0235-6880/97/12 919-04 $02.00

undisturbed form, we do not take into account the interaction between separate parts of the scattering medium. Let us consider, how the degree of breaking the layer affects the radiative characteristics, taking into account the scattering phase function shape, single scattering albedo, and the optical length of the medium. Let us characterize the degree of breaking the medium m by the ratio of the optical section $\tau_{y1}\times\tau_{z1}$ of one part of the medium to the optical section $\tau_{y0}\times\tau_{z0}$ of the whole medium. Considering the simplest situation, breaking of one cloud into two parts of the same optical length as the initial cloud, one can suppose the transmittance of the whole cloud to be equal to the sum of transmittances of its parts, due to the additive principle as, for example, is in the model of cloudiness as "screens".

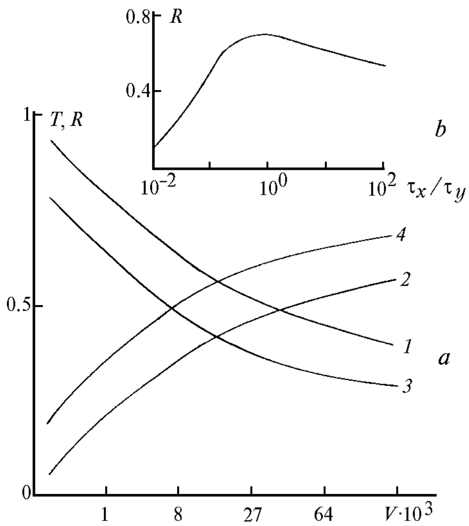

FIG. 1. Transmission T and reflection R of the cloud of the optical size $\tau_x\times\tau_y\times\tau_z$ as functions of the optical volume at $\Lambda = 1$, scattering phase function C1. *Transmission (1 and 3) and reflection (2 and 4) at* $\tau_x:\tau_y$ = 1:3.5 *and* 1:1 respectively *(a). Reflection R as a function of τ_x/τ_y (b).*

It is known that the additive principle may not hold in the aforementioned model if energy exchange between "screens" occurred. However, the analysis of experimental data shows that there is no unambiguous relationship between the transmittance and cloud amount even at the absence of interaction between separate clouds. The results obtained show that the change of the cross size of a medium with a fixed length leads to the change of the budget of radiation propagating in a limited volume of a disperse medium, and hence, to the change of the transmittance value. Since the radiation fluxes to upper and lower hemispheres are determined when calculating the radiation budget, then, when breaking the medium into separate non-interacting parts an increase in the radiation transmission should be observed due to an increase of the fraction of light multiply scattered to the lower hemisphere.

This effect is illustrated in Fig. 2*a* the results of calculations presented in this figure show the action of the clearing-up effect in the specific cases. The effect of breaking on the transmission of radiation is small at small optical lengths ($\tau_x \sim 1$), the effect increases as τ_x and absorption grow.

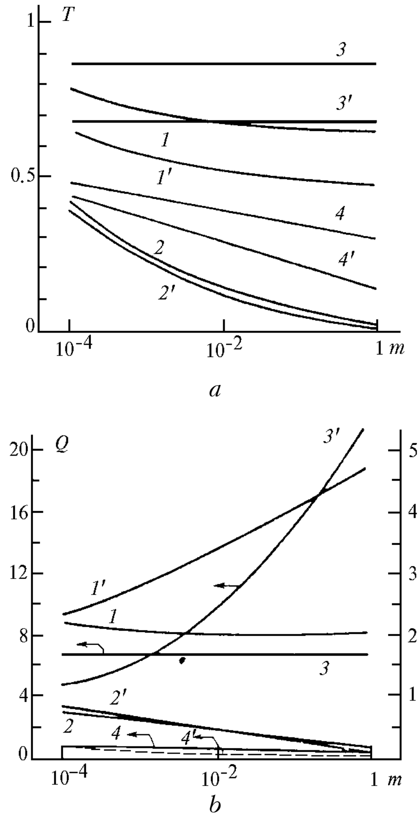

FIG. 2. Transmission T (a) and the ratio Q (b) as functions of the degree of breaking the disperse medium m; $\tau_{x0} = 1$, $\Lambda = 1$, $g = 0$ *(1);* $\tau_{x0} = 1$, $\Lambda = 0.7$, $g = 0$ *(1′);* $\tau_{x0} = 20$, $\Lambda = 1$, $g = 0$ *(2);* $\tau_{x0} = 20$, $\Lambda = 0.7$, $g = 0$ *(2′);* $\tau_{x0} = 1$, $\Lambda = 1$, $g = 0.77$ *(3) (cloud scattering phase function*[7] C1*);* $\tau_{x0} = 1$, $\Lambda = 0.7$, $g = 0.77$ *(3′);* $\tau_{x0} = 20$, $\Lambda = 1$, $g = 0.77$ *(4);* $\tau_{x0} = 20$, $\Lambda = 0.7$, $g = 0.77$ *(4′).*

One more significant component of the radiation budget is the albedo of cloud systems, so the relationship between the transmission and reflection when breaking the medium is interesting. The ratio

$$Q = T/R ,$$

shown in Fig. 2*b* weakly increases at $\Lambda = 1$, and at the presence of absorption the behavior of this dependence can change as the absorption in the medium changes. That can be explained by the change of the relationship between the radiation budget components (the increase of the fraction of absorbed radiation).

Breaking of a disperse medium with absorption leads to one effect, more which is of extreme importance for the energy of the atmosphere. The matter is that a sharp decrease of the portion of absorbed radiation occurs at the increase of the cloud amount accompanied by a decrease in the cross size of an individual cloud (Fig. 3).

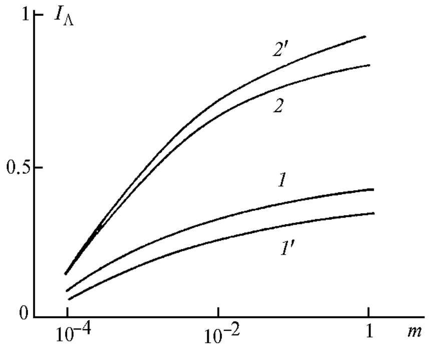

FIG. 3. Absorbed energy as a function of the degree of breaking the disperse medium m; $\Lambda = 0.7$; $\tau_{x0} = 1$ (*1, 1′*), 20 (*2, 2′*), $g = 0$ (*1, 2*), 0.77 (*1′, 2′*).

As follows from the data presented the change of the scattering phase function shape does not affect the qualitative behavior of the curves in all cases considered. Since in general case the clearing-up value depends on the medium volume, then, as it was shown above, it is necessary to take into account the change of the medium size.

It order to reveal peculiarities in the radiation transfer in the inhomogeneous stratified media, the radiation transfer was studied in a spatial-limited medium of a parallelepiped shape with different optical size τ_x, τ_y, τ_z at the number of layers equal to 3, and the single scattering albedo[6] $\Lambda = 1$.

Monodisperse suspensions of polystyrene latex with the particle size 0.1, 0.95 and 1.5 μm in water were used as model media. The following layer combinations were studied: 123, 132, 213, 231, 312, 321, as well as each layer separately. Measurements were carried out of the intensity of radiation passing through the medium, reflected from the medium and escaping through the sides. The effect of the spatial limits of the medium on the radiation budget was studied at the following values of the optical size of the medium: $\tau_{x1} = 5$; $\tau_{x2} = \tau_{x3} = 10$; $\tau_{y1} = 15$; $\tau_{y2} = \tau_{y3} = 30$; $\tau_z = 10$; and $\tau_{z2} = \tau_{z3} = 20$. The values of transmittance T, reflection R and output through the side surface B were the following for each layer:

$T_1 = 0.189$, $T_2 = 0.553$, $T_3 = 0.529$;

$R_1 = 0.445$, $R_2 = 0.124$, $R_3 = 0.118$;

$b_1 = 0.366$, $b_2 = 0.323$, $b_3 = 0.352$.

The results of subsequent investigations of the radiation transfer through a stratified inhomogeneous medium are presented in Fig. 4. The enhanced outgoing of radiation through the side is observed for the layer combination 132 at the optical thickness 0–3 in comparison with the combination 231. Subsequent increase of τ weakly affects the intensity value, hence the integral radiation flux outgoing through the side surface of the stratified medium is significantly lower than in the layer combination 231. Let us note that the layers 2 and 3 are characterized by strongly elongated scattering phase function. As follows from Fig. 4*a*, the curve 321 has the same shape as the dependence 231 at a bit lower intensity values. The rearrangement of 2 and 3 between each other weakly affects the outgoing of radiation through the side surface. Therefore, the output of radiation through the sides is characterized by three types of distributions, and the distribution character determines the layer which is situated first in the layered medium. At the same time, the distribution of radiation coming through the side keeps its own peculiarity in each case.

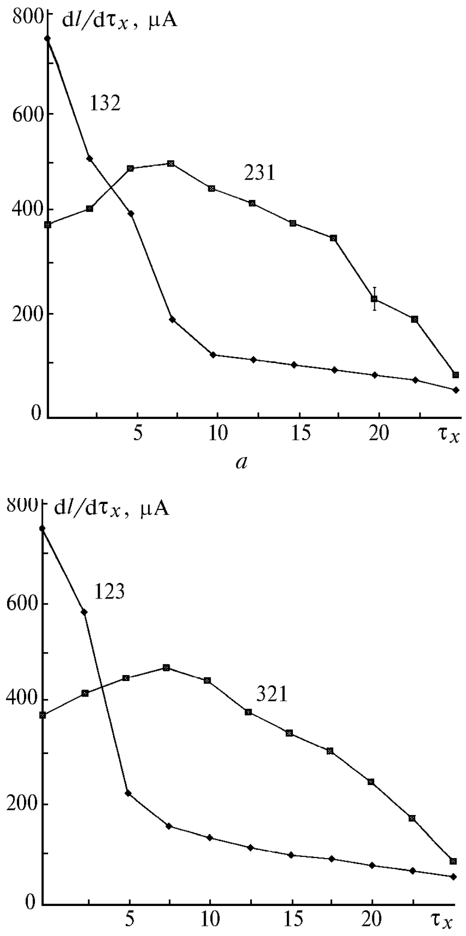

FIG. 4. Distribution of the intensity of radiation outgoing through the side surface of the scattering medium. Numbers show the order of alternating the layers. $\tau_{x1} = 5$; $\tau_{x2} = \tau_{x3} = 10$; $\tau_{y1} = \tau_{z1} = 15$; $\tau_{y2} = \tau_{z2} = \tau_{z3} = \tau_{z3} = 30$.

The technique developed was used for calculation of the radiation transfer in stratus cloudiness as an example. The three-layer cloud model was used for calculation of the energy characteristics of radiation. Each layer was characterized by the following parameters. The upper, large-droplet layer had the scattering phase function presented in Ref. 7, for $\rho = 100$, $n = 1.33$, $\tau_{x1} = 7$, where ρ is the Mie parameter, and n is the refractive index. The medium layer had the scattering phase function corresponding to the C1 distribution,[7] $\tau_{x2} = 7$. The lower layer was characterized by the scattering phase function corresponding to the C3 particle size distribution,[7] $\tau_{x3} = 6$. The transmission and reflection coefficients of the three-layer cloudiness were calculated for this model depending on the cross-section geometrical size.

As follows from the results presented in Fig. 5, very strong dependence (by one order of magnitude) of the transmission T and reflection R coefficients on the cross-section optical size of cloudiness is observed.

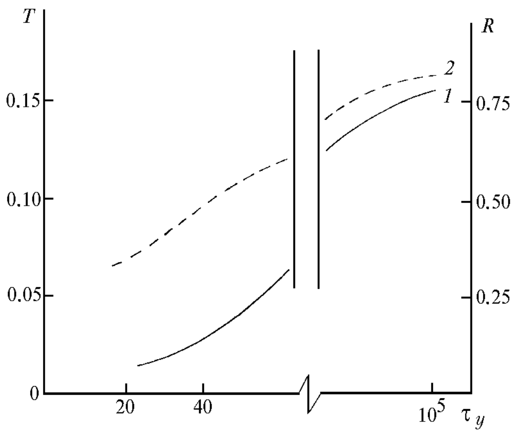

FIG. 5. Transmission T (curve 1) and reflection R of the three-layer cloudy medium as functions of the cross-section optical size $\tau_y = \tau_z$.

Thus, one can draw the following conclusions from the results obtained:

1. Clouds with the maximum degree of symmetry make the highest contribution into the albedo of the cloudy atmosphere.

2. The effect of "anomalous" transmission of radiation in broken cloudiness is the consequence of the effect of clearing-up the layer of the disperse medium when breaking it and of a sharp decrease in the absorption at an increase of cloud amount accompanied by a decrease of the optical size of a separate cloud.

3. The upper cloud layer produces the main effect on the values of the coefficients T and R in the stratus cloudiness.

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