RADIATION EFFECTS IN BROKEN CLOUDINESS

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Received July 20, 1994

This paper discusses the state and prospects in the theory of radiative transfer in a broken cloudiness. It shows that the effects connected with stochastic cloud geometry may strongly affect the radiative transfer. This must be accounted for when interpreting the albedo paradox and anomalous absorption in the near–IR spectral range as well as in radiation modules of GCMs and in algorithms for retrieving an albedo and cloud–cover parameters from satellite measurements.

1. INTRODUCTION

Climate anywhere on the Earth is the product of a large number of processes with complex feedback mechanisms. Among those, of a particular concern are the processes describing the interaction between the cloud and radiation fields, in the light of the evidences from certain numerical studies of strong sensitivity of climate to these processes (see, e.g., Refs. 1 and 2). The cloud–radiation interaction is intensively investigated through the World Climate Research Program and its different subprograms, such as GEWEX (the Global Energy and Water Cycle Experiment) and FIRE (First International Satellite Climatology Project Regional Experiment).

Clouds are a major determinant of the planetary albedo, as reflecting an appreciable portion of incoming solar radiation backward, into outer space. Through this process, they control the heating of the Earth's surface by solar radiation and, simultaneously, inhibit its cooling, reemitting the thermal radiation backward to the surface. Higher and cooler clouds emit much less thermal radiation than lower and warmer clouds, so that the former may even warm the climatic system.[3]

As known, a 1% increase in the mean albedo of the atmosphere–underlying surface system (an absolute increase of 0.003 in albedo) may cause the surface equilibrium temperature decrease of 0.5°C (see, e.g., Refs. 4–6). A 10% increase in the albedo (from 0.30 to 0.33) would produce the global cooling of 5°C, thus driving the climate to the Ice Age. Obviously, such large errors in the determination of albedo are unpermissible on the spatiotemporal scales of climate.

However, now existing climate models, based on general circulation models (GCMs), may produce shifts in albedo up to 10% or more for sufficiently large regions, once the clouds contain the observed amount of liquid water. The point is that GCM radiation moduls use the simplest model of clouds as horizontally homogeneous plane–parallel layer (plane–parallel model) and disregard the extreme horizontal inhomogeneity of cloud optical properties, caused by

– cloud–field stochastic geometry;

– fluctuations in water content, drop size spectrum, and phase composition (liquid water or ice crystals) inside individual clouds.

The term "inhomogeneous clouds" is usually taken in the sense that the optical parameters have horizontal gradients in at least one direction. This inhomogeneity, together with the nonlinear relationship between radiative characteristics and optical parameters, is responsible for the difference between the mean albedo of cloud field and albedo of plane–parallel layer with mean values of optical characteristics. To eliminate this shift and obtain realistic values of albedo, GCMs are forced to employ unrealistically small liquid–water contents.[7]

Obviously, to eliminate correctly the shift, it is necessary to answer the question: How accurate do the plane–parallel cloud models estimate the albedo and brightness fields of reflected radiation? These estimates are used as a basis for approximations employed in existing GCMs and in algorithms of retrieving the cloud parameters from satellite data. It should be remembered, however, that GCMs and retrieval algorithms deal with quite different spatial scales. The retrieval algorithms normally assume the brightness to be only a function of the cloud properties within each pixel falling within the receiver's field of view and not exceeding 1 km in extent. In contrast, each time step in a GCM is connected with the determination of upward and downward fluxes averaged over the regions 100 km as large.

The above questions pose the following problems, fundamentally important for the development of radiative transfer theory in inhomogeneous media.

– Development of optical models of inhomogeneous clouds, adequately accounting for the random geometry and inhomogeneous internal structure of clouds.

– Using the equation of transfer and the optical models developed, to elaborate the methods for calculating the linear functionals of the mean intensity, the albedo, in particular.

Although the distinction is somewhat arbitrary, the models of inhomogeneous cloud systems can be divided into two groups:

1) models of stratiform clouds, based on the plane–parallel layer and characterized by optical parameters varying in at least one horizontal direction due to internal inhomogeneity and/or irregular boundaries;

2) models of cumulus, taking into account their amount, extent, shapes, and spatial arrangement (stochastic geometry) as well as the variations of optical properties inside the clouds. The fields of cumulus with stochastic geometry and deterministic internal structure will be called broken cloudiness.

The present paper discusses briefly the state and the prospects of the theory of radiative transfer in broken clouds, which is now under intensive investigation in the Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Sciences. The paper reviews existing models of broken cloudiness, methods of solution of the transfer equation as well as evaluates the effects of stochastic cloud geometry on mean radiant fluxes and brightness fields. Constructing the models, the spatial

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variations of size spectrum of cloud particles were not considered.

2. STOCHASTIC MODELS OF BROKEN CLOUDS

The optical model of cumulus with stochastic geometry and deterministic internal structure is specified in the layer Λ: $0 \le z \le H$ as the random scalar fields of the extinction coefficient $\sigma(\mathbf{r})k(\mathbf{r})$, single scattering albedo $\lambda(\mathbf{r})k(\mathbf{r})$, and scattering phase function $g(\mathbf{r}, \omega, \omega')k(\mathbf{r})$. Here $\sigma(\mathbf{r})$, $\lambda(\mathbf{r})$, and $g(\mathbf{r}, \omega, \omega')$ are known nonrandom functions, while $k(\mathbf{r})$ is the random indicator field

$$k(\mathbf{r}) = \begin{cases} 1\ , \ \mathbf{r} \in G \\ 0\ , \ \mathbf{r} \notin G\ , \end{cases} \tag{1}$$

where G is the random set of points in Λ at which the cloud matter appears, i.e., $k(\mathbf{r}) = 1$ inside a cloud and $k(\mathbf{r}) = 0$ outside it. The statistics of the optical parameters of broken clouds is determined by the probabilistic properties of the field $k(\mathbf{r})$. The aerosol and molecular scattering coefficients are much smaller than corresponding cloud parameters and, therefore, can be neglected within the layer Λ.

The construction of a physical model of $k(\mathbf{r})$ is an independent and very complicated problem, the solution of which must be based on the fundamental equations of cloud formation and extensive data of field observations. At present this problem is not solved, so researchers are forced to use mathematical models of $k(\mathbf{r})$. The models typically assume an ensemble of individual clouds with a particular geometric shapes that are distributed stochasticly in space. In such a model, one of the main questions is the law of spatial distribution of the clouds. We will discuss this issue briefly.

It is known[8] that the main processes responsible for formation of cumulus are the thermal convection and turbulent exchange. For plain areas there is no experimental evidence for the existence of relations between spatial inhomogeneities of the surface and convective flows, what makes it possible to neglect the inhomogeneity. Exceptions must be made for mountain regions, coastal regions, etc., where the fields of meteorological and physical parameters of the atmosphere and surface typically have large horizontal gradients.

We assume that the mean distance between clouds is large, and for this reason the dynamical interaction of clouds (heat, moisture, momentum exchange, etc.) can be neglected. If the surface and thermodynamic parameters of the atmosphere up to the condensation level are horizontally homogeneous, then on the average there are no physical causes which favor the more intensive processes of cloud formation in some regions over others (between the levels of condensation and free convection). For this reason, the assumption about the statistical independence and homogeneity of cumulus distribution can be made within the layer. This assumption is justified by results of Ref. 9, where based on radar data it is concluded that the spatial distribution of dynamically noninteracting clouds is well approximated by the Poisson distribution.

Statistical characteristics of cloud fields, generated by Poisson point fluxes, are sufficiently well studied.[10–13] For such random fields, an approximate formula is obtained for splitting the functionals of special form, without which it is impossible to deduce the equations for intensity moments (see Section 3). Figure 1 shows a cloud field generated by Poisson point flux in space. Note, what "wild" structures are obtained for such a simple model. Also, it is proposed to use the Gaussian fields to construct cumulus models close to the Poisson models.[14]

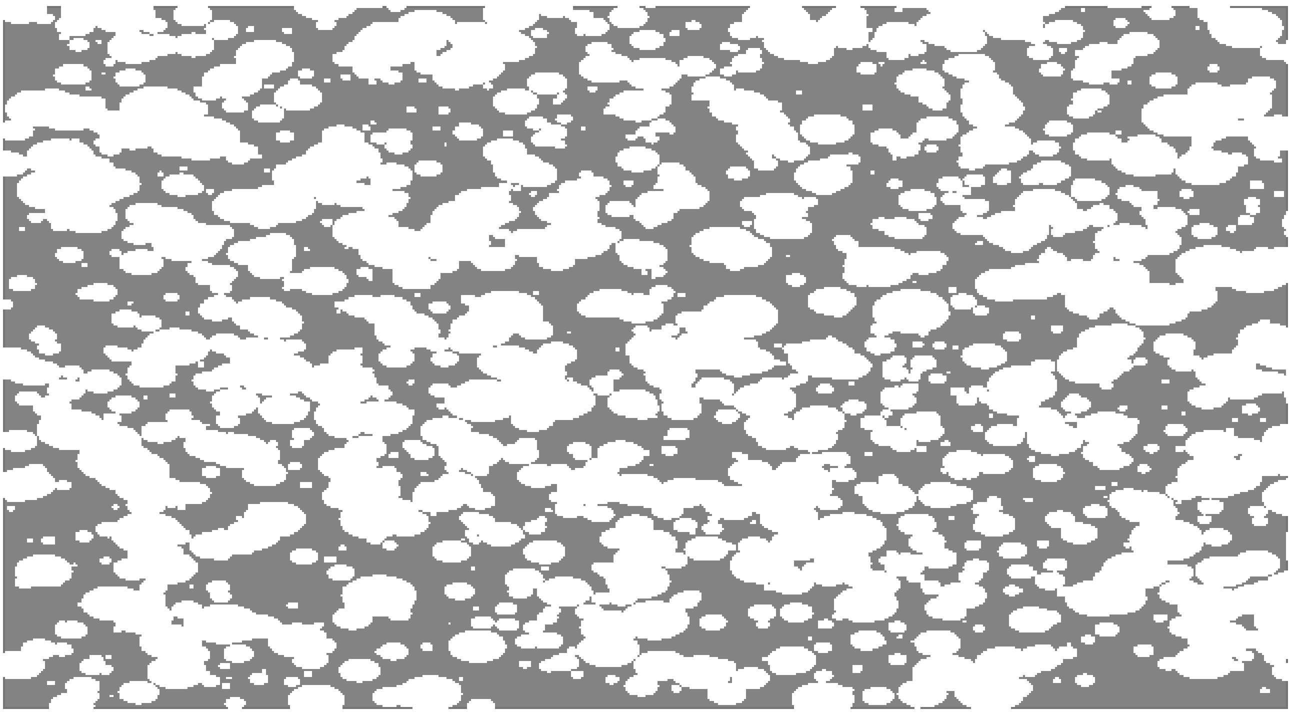
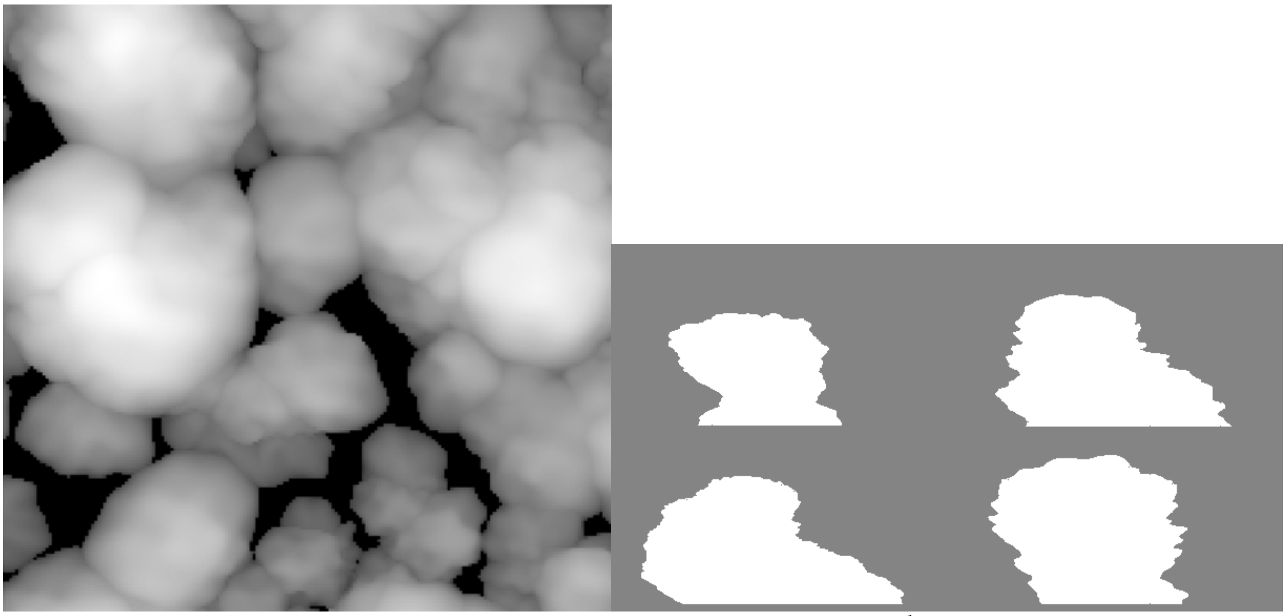


FIG. 1. A cloud field in the area of $25\times\times25$ km^2 *generated by Poisson point flux in space (top view). Individual clouds are approximated by paraboloids of revolution; they have exponential size–distribution function.*

Real cumulus have a very odd and irregular geometry, so that the use of simplest geometric bodies (such as truncated paraboloids, parallelepipeds, spheres, and so on) may appear to be quite a crude approximation and lead to uncertainties in calculating the flux and brightness field statistics of broken clouds. To evaluate these uncertainties, it is necessary to develop more complex models taking into account the random geometry of cumulus. We propose to construct such models based on the Poisson field and a sum of n independent Gaussian fields with decreasing variances and correlation radii (PG_n model).[15] Figure 2 presents the clouds simulated by a computer using the PG_n model. As is seen, highly interesting pictures are obtained, sufficiently close to actually observed cumulus. Statistical characteristics of the indicator field in the PG_n model are insufficiently investigated; they require further studies.



a *b*

FIG. 2. A cloud field generated by the Poisson field and a sum of independent Gaussian fields (PG_n model for $n = 6$) in the area of $2\times\times2$ km^2*: top view, the picture brightness is proportional to the cloud optical depth (a) and vertical cross sections of individual cumulus (b).*

3. METHODS OF SOLUTION

Methods of solution are based on the stochastic radiative transfer equation of the form

$$\omega\Delta I(\mathbf{r},\ \omega) + \sigma(\mathbf{r})k(\mathbf{r})I(\mathbf{r},\ \omega) = \lambda(\mathbf{r})\sigma(\mathbf{r})k(\mathbf{r}) \int_{2\pi} g(\mathbf{r},\ \omega,\ \omega')\ \mathrm{d}\omega', \quad (2)$$

where $I(\mathbf{r},\ \omega)$ is the random specific intensity at the point $\mathbf{r} = (x,\ y,\ z)$ in the direction $\omega = (a,\ b,\ c)$. Depending on whether Eq. (2) is averaged numerically or analytically, the existing methods of calculating the statistical characteristics of radiation can be divided into two groups.

1. Numerical simulation of cloud and radiation fields. This method is based on numerical simulation of a sample cloud field using a computer, exact solution of Eq. (2) for each sample, and statistical processing of the obtained ensemble of radiation fields. Each sample of the cloud field is a three–dimensional scattering medium with a very complex irregular geometry. At present, the Monte Carlo method is the only technique for solving the radiative transfer equation in such media. However, the cost of the computation of the radiation's statistics is often prohibitive, because numerical solution of Eq. (2) itself is expensive. The efficiency of the Monte Carlo method is appreciably increased by randomization,[16] that is, introduction of additional randomness. It is shown that the estimates for the linear functionals of the solution of Eq. (2) can be obtained by simulating the number $m \geq 1$ of trajectories for each cloud field. The choice of optimal m needs for special consideration. In the Poisson cloud models, the mean fluxes and the histograms of angular distributions are computed optimally at $m = 1$ (Ref. 12). It is not necessary to obtain a rigorous solution of Eq. (2) for each cloud sample, so averages over both the ensemble of cloud field samples and trajectories can be computed during a reasonably long time. Modeling of the free path can be made much less expensive by employing the method of maximum cross section.[17]

Obviously, the method of numerical simulation can be used in any broken cloud model where samples of a cloud field can be constructed numerically on a computer. This is one of the main advantages of the method, since it opens a wide opportunities for improving the stochastic optical models based on field data. Further, the method considered is accurate in the sense that the statistical characteristics of the radiation are calculated without approximations and simplifications. Consequently, the estimates can be obtained with a preset accuracy. For this reason this method can be used to assess the accuracy and applicability of approximate methods based on analytical averaging of Eq. (2) over an ensemble of cloud fields. The method is deficient primarily in that computations of the mean intensity in a given direction or variance and correlation functions of fluxes (intensity) require much computer time, even with very powerful computers. The statistical simulation algorithms for computation of the mean fluxes of visible solar radiation were first developed and implemented in the model generated by the Poisson point fluxes in space.[18]

2. Method of closed equations. The closed systems of equations for the mean specific intensity[19] and spatial correlation functions of solar radiation[20] were derived through the spatial averaging of the stochastic transfer equation. The system of equations for the mean specific intensity is solved in the transport approximation;[21] the results of calculations of the mean fluxes and angular distributions of reflected and transmitted radiation are presented in Refs. 22 and 23. These papers first showed the possibility, in principle, of deriving the closed equations for specific intensity moments from the stochastic transfer equation, and this is the principal scientific value of these studies. Appreciating the importance of the results obtained in Refs. 19–23, it should, however, be noted that the equations for the specific intensity moments are obtained in the nonconstructive (samples of a cloud field cannot be constructed) broken–cloud model by averaging over space rather than over an ensemble. In deriving the equations a number of assumptions are used, which either have unclear physical and probabilistic meanings or limit their application. For example, the transfer of spatially bounded beams from artificial sources of radiation is excluded from consideration. Since the model is nonconstructive, it is impossible to relate accurately the model input parameters to the statistical characteristics of cloud fields determined experimentally. This introduces serious difficulties into making comparisons between the theory and experiment and interpretation of the calculational results.

Further step in developing the radiative transfer theory in broken clouds was done in Ref. 24, where closed equations for the moments of intensity of short–wave optical radiation were obtained in the Markov approximation by averaging of Eq. (2) over the ensemble of cloud field samples. In a particular case of homogeneous boundary–value conditions, these equations are equivalent to equations of Refs. 19 and 20. Thus, instead of a set of insufficiently clear assumptions used in Refs. 19 and 20, the only assumption can be retained about factorizing the n–dimensional probability of cloud presence for the ordered sequence of points, the assumption that has clear probabilistic meaning.

However, Ref. 24 did not raise the question about how to construct the random fields with factorizable n–dimensional probability of cloud presence for an ordered sequence of points. This issue is of key importance from the viewpoint of mathematical validity of equations for the intensity moments. In Refs. 25 and 26 it is shown for the statistically homogeneous Poisson fields that this probability is factorized if the points lie on one straight line[25] (Poisson point flux in space), or on a broken line, coordinates of "node" points of which form monotonic sequences (Poisson point flux on straight lines). The above said indicates that the equations for intensity moments in the Markov approximation are valid in the Poisson models of cloud fields. This implies that the accuracy and applicability of these equations can be readily verified by comparing them with appropriate calculations using a method of numerical simulation. This comparison shows a good accuracy of equations for the mean intensity.[27] It is practically impossible to make quantitative comparisons for the variance and correlation function of intensity, since high–precision numerical simulations are unavailable now; we can only say about a qualitative good agreement between the results.[28] It is important also to note that the constructiveness of the Poisson cloud–field models allows us to relate the model inputs to field data, thus improving substantially our understanding of how solar and thermal radiation characteristics respond to the effects caused by the stochastic geometry of clouds.

The equations for intensity moments in the Markov approximation are also obtained in Refs. 29 and 30, but using different way where in addition the formula for correlation splitting is given, and the equations for non–Markovian statistics are deduced. However, the formula was derived there without strict mathematical foundation and, moreover, no random fields are yet known for which it would be at least approximately valid. The construction of such random fields is highly interesting and important problem, whose solution requires additional studies.

For statistically homogeneous cloud fields with uniform optical characteristics of clouds, the algorithms are developed for the solution of equations for the first and second moments of intensity, obtained in the Markov approximation by the Monte Carlo method (see, e.g., Refs. 12 and 13 and bibliography therein). The comparison of computed statistical characteristics of solar radiation with available field data shows quite reasonable agreement; therefore, these equations can be used, at least as a first approximation, for studying the flux statistics and brightness fields in broken clouds.

4. THE MEAN FLUXES OF SOLAR RADIATION

The radiation field of broken clouds is formed as a result of random effects associated with the random geometric structure of a cloud field:

1) the incident parallel flux of solar radiation can penetrate, and the direct and scattered radiation can leave a cloud layer through non–horizontal bounding surfaces of an individual cloud;

2) incident radiation can be screened by surrounding clouds. The mutual shading and radiative interaction of clouds can occur, the latter because a fraction of radiation exiting through the cloud sides can be multiply scattered by neighboring clouds.

The effects in the first group are connected with finite horizontal cloud size, while those in the second are caused by the fact that each cloud is not isolated in the space; it belongs to the cloud ensemble. It is obvious that these effects are missing completely in the plane–parallel cloud models and are partly allowed for in an isolated equivalent cloud model. As to the cloud field model in the form of an ensemble of clouds regularly located in space, it incorporates the effects mentioned above but they are nonrandom. Since the radiation field depends nonlinearly on the number of clouds and their locations in space, these effects are taken into account incorrectly. Only when broken clouds are modelled as a statistical ensemble, the effects in both groups are accurately taken into account. These effects are responsible for quantitative and qualitative features of the radiative characteristics of cloud fields with a random geometry.

Let the parallel unit flux of solar radiation be incident upon the cloud layer in the direction $\boldsymbol{\omega}_{\otimes} = (a_{\otimes}, b_{\otimes}, c_{\otimes})$ ($c_{\otimes} = -\cos\xi_{\otimes}$ is the solar zenith angle). The optical characteristics of the cloud layer correspond to the C_1 cloud[31] and wavelength of 0.69 μm. Below, angular brackets are used to designate mean characteristics of the radiation field.

Obviously, the effects caused by finite horizontal size of clouds will depend on the parameter $\gamma = H/D$ with the cloud thickness H and the mean (effective) cloud size D. We have $\gamma < 1$ for stratus and $\gamma \sim 1$ for cumulus. For calculation of the mean albedo $\langle R_{\mathrm{St}} \rangle$ of stratus covering partially the sky, we use the formula which readily follows from the equations for the mean intensity at $\gamma \to \infty$, namely

$$\langle R_{\mathrm{St}}\rangle = N{\cdot}R_{\mathrm{c}} + (1 - N)\, R_{\mathrm{s}}\,, \tag{3}$$

where R_{c} and R_{s} are the albedos of the plane–parallel cloud layer and clear sky, respectively. The values of R_{c} and R_{s} are normally assumed to be independent of cloud fraction N. Analogous formulas can be written for the mean direct $\langle S_{\mathrm{St}}\rangle$ and diffuse $\langle Q_{\mathrm{s,St}}\rangle$ transmitted radiation. Neglecting the stochastic geometry of upper cloud boundary and variations of water content inside stratus, this formula is quite accurate for calculation of the mean fluxes of solar radiation.[32]

For simplicity, the impact of atmospheric aerosol and reflection from underlying surface will be neglected, i.e., $R_{\mathrm{s}} = 0$. Let us take $\xi_{\otimes} = 0°$ and cloud fraction $N = 0.5$, then $\langle S\rangle = 0.5[1 + \exp(-\sigma H)] \approx 0.5$, $\langle Q_{\mathrm{s}}\rangle + \langle R\rangle \approx 0.5$, where $\langle R\rangle$, $\langle S\rangle$, and $\langle Q_{\mathrm{s}}\rangle$ are the mean albedo and the mean direct and diffuse transmitted radiation in cumulus, respectively. In plane–parallel cloud layer with the mean optical depth $\langle\tau\rangle = N\sigma H$ (the mean medium) $S(\langle\tau\rangle) = \exp(-N\sigma H)$. As far as the cumulus are optically thick, then, except for very small and large cloud fractions N, the inequality $\langle S\rangle > S(\langle\tau\rangle)$ holds. Obviously, the diffuse fluxes will be strongly diverse too, since for $N = 0.5$ cumulus scatter only half the incident light, while the mean medium scatters radiation almost totally. For this reason, it is reasonable to compare the mean albedos of cumulus and equivalent stratus. The equivalence here is taken in the sense that the cloud modes differ only in the mean horizontal cloud size.

Figure 3 shows the effective cloud amount $N_{\mathrm{e}} = \langle R\rangle/R_{\mathrm{c}}$ (Refs. 33 and 34). Under the above assumptions, formula (3) gives that $N_{\mathrm{e,St}} \equiv N$ for stratus; it is independent of cloud micro– and macroparameters and solar zenith angle whose value varies with season, time of day, and latitude. If the sun is at zenith, then irregardless of cloud fraction we have $N_{\mathrm{e}} \equiv N_{\mathrm{e,St}}$ or $\langle R\rangle < \langle R_{\mathrm{St}}\rangle$ (Fig. 3, curve *1*). This inequality is explained as follows. It is obvious that at $\xi_{\otimes} = 0°$ the mean fraction of scattered radiation is the same for stratus and cumulus, i.e., $\langle R\rangle + \langle Q_{\mathrm{s}}\rangle = \langle R_{\mathrm{St}}\rangle + \langle Q_{\mathrm{s,St}}\rangle$. In stratus, the radiation almost totally exits through the cloud tops and bases, whereas in cumulus a considerable portion of radiation can exit through the sides of the large number of individual clouds. On the average, radiation emerging from the sides has undergone fewer scattering events than radiation exiting through the cloud tops and bases. Because of a very pronounced forward peak of the phase function, the major fraction of radiation exiting through cloud sides contributes to the transmittance, so that $\langle Q_{\mathrm{s}}\rangle > \langle Q_{\mathrm{s,St}}\rangle$ and, hence, $\langle R\rangle < \langle R_{\mathrm{St}}\rangle$. At large cloud fractions these inequalities become weaker due to the radiative interaction between clouds. For a given N with an increase of $\xi_{\otimes}$ the value of $1 - \langle S\rangle$ remains practically unchanged for stratus. Due to illumination of the large number of sides, it increases substantially for cumulus. Consequently, $\langle R\rangle + \langle Q_{\mathrm{s}}\rangle > \langle R_{\mathrm{St}}\rangle + \langle Q_{\mathrm{s,St}}\rangle$ and at zenith angles larger than some $_{\otimes}$ value, the reverse inequality $\langle R\rangle > \langle R_{\mathrm{St}}\rangle$ is fulfilled (Fig. 3, curve *3*). For $N = 0.5$ the mean albedo deviation $\delta R = \dfrac{(N_{\mathrm{e}} - N)}{N} \times 100\%$ ranges from -16 ($\xi_{\otimes} = 0°$) to 30% ($\xi_{\otimes} = 60°$). Thus, for cumulus formula (3) either overestimates (for sun near zenith) or underestimates (for sun near horizon) the mean albedo. It is worth noting that the effective amount of cumulus depends on their optical properties, e.g., on optical depth.

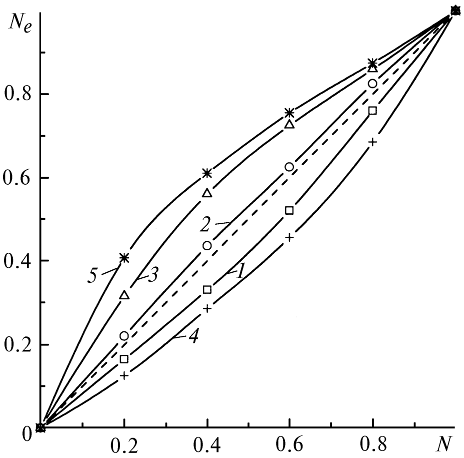


FIG. 3. The dependence of the effective cloud amount on cloud fraction for $\sigma = 60\ \mathrm{km}^{-1}$, $H = 0.5$ km, *and* $D = 0.25$ km; $\xi_{\otimes} = 0$ (*1*), 30 (*2*), *and* 60°(*3*)*; Ref. 35* (*4*) *and Ref. 36* (*5*)*; dashed line refers to stratus.*

Schmetz[35] has proposed a parametrization of radiative transfer in which the mean albedos of cumulus are assumed to be equal to the corresponding albedo of some equivalent parallelepiped cloud, whose geometric size and optical thickness increase with increasing cloud fraction. According to this parametrization, N_{e} depends weakly on $\xi_{\otimes}$, and for short–wave radiation $N_{\mathrm{e}} < N$ everywhere (Fig. 3, curve *4*). This contradicts the above results having clear physical interpretation, because Schmetz's parametrization neglects screening of incident radiation by sides of numerous clouds, mutual shading, and multiple scattering of light between clouds (radiative interaction).

The solar radiation transfer in a horizontally inhomogeneous cloud field consisting of the given number of identical clouds regularly located in space was considered by Harshvardhan.[36] The problem was solved under the assumption that diffuse radiation was incident upon the upper boundary of the cloud layer. Because the source is isotropic in hemisphere, the results can be compared with our calculations for some intermediate solar zenith angle $_{\otimes} < 90°$. At a very large values ($_{\otimes} > 60°$) more or less satisfactory coincidence of the results (see Fig. 3, curves *3* and *5*) is observed. The value of N_{e} determined by the parametrizations of Refs. 35 and 36 is independent of the optical properties of clouds, what is physically meaningless.

The solar radiative fluxes depend on many parameters, thus necessitating the investigation into not only the mean fluxes but also their partial derivatives. The latters allow one to estimate quantitatively the sensitivity of fluxes to variations of cloud field parameters and to identify the most important cloud characteristics influencing on the radiation field. Of particular interest is the partial derivative of the mean albedo with respect to cloud fraction, because it is used to estimate the sensitivity δ of the radiation budget to variations of cloud fraction.[37] By definition,

$$\delta = -\frac{S_0}{4}\frac{\partial\langle R\rangle}{\partial N} - \frac{\partial\langle F_{\infty}\rangle}{\partial N}\,, \tag{4}$$

where S_0 is the solar constant, $\langle R\rangle$ is the mean system albedo, and $\langle F_{\infty}\rangle$ is the mean flux of outgoing thermal radiation, all spectrally integrated. The albedo effect dominates when $\delta < 0$, while greenhouse effect dominates when $\delta > 0$.

From Eq. (3) it follows for the equivalent stratus that

$$\frac{\partial \langle R_{\mathrm{St}} \rangle}{\partial N} = R_c - R_s\,, \qquad \frac{\partial \langle Q_{s,\mathrm{St}} \rangle}{\partial N} = Q_c - Q_s\,, \tag{5}$$

where Q_c and Q_s are the transmission, for diffuse radiation, of plane–parallel clouds and clear sky, respectively. These derivatives are independent of N and D and equal to the corresponding fluxes computed for $N = 1$ (Fig. 4*a*). The mean fluxes in cumulus depend nonlinearly on the cloud fraction (Figs. 3 and 4*a*), so that the variations of N and $\xi_\otimes$ may cause these derivatives to vary several fold, $\frac{\partial\langle Q_s\rangle}{\partial N}$ can alter its sign, while $\frac{\partial\langle R\rangle}{\partial N}$ can change from a monotonically increasing function for $\xi_\otimes < {}_\otimes$ to monotonically decreasing for $\xi_\otimes > {}_\otimes$, ${}_\otimes \sim 30°$ (Fig. 4*b*). The flux $\langle Q_s\rangle$ for the entire range of $\xi_\otimes$ and the mean albedo for large solar zenith angles $\xi_\otimes$ are most sensitive to changes in cloud fraction when N is small, where the corresponding derivatives are maximum. At small solar zenith angles, the albedo exhibits its maximum variability for large N values, but for intermediate N the albedo $\frac{\partial\langle R\rangle}{\partial N}$ depends weakly on $\xi_\otimes$ only.

The derivatives of the mean fluxes with respect to the cloud horizontal size D have their maxima as functions of cloud fraction at $N \le 0.5$. The maximum shifts toward smaller N as $\xi_\otimes$ increases (Fig. 4*c*). Therefore, $\langle Q_s\rangle$ and $\langle R\rangle$ are most sensitive to the variations of D when $N \sim 0.2$–0.5; experimental data[38] evidence that these N values are typical for fair–weather cumulus. As $\xi_\otimes$ increases from 0 to 30°, $\frac{\partial\langle R\rangle}{\partial D}$ alters its sign and for ${}_\otimes < 30°$ the mean albedo becomes independent of D; it is equal to the mean albedo of stratus.

The derivatives with respect to N and D are approximately of one and the same order (Figs. 4*b* and *c*), with the mean albedo being more sensitive to the N variations than to the D variations. For small cloud fractions, $\langle Q_s\rangle$ is more sensitive to variations of cloud fraction, while for intermediate and large cloud fractions it behaves similarly for variations of both N and D. Calculations of the derivatives $\frac{\partial\langle Q_s\rangle}{\partial s}$ and $\frac{\partial\langle R\rangle}{\partial s}$ have shown that these are 2 to 3 orders of magnitude smaller than the derivatives with respect to N and D, i.e., the mean radiation regime of cumulus depends weakly on the extinction coefficient. To change the mean fluxes by the same amount as variations $\Delta N \sim 0.1$, the extinction coefficient must change by $\Delta\sigma \sim 10$–100 km^{-1}. Because of so small variations of $\langle Q_s\rangle$ and $\langle R\rangle$ with σ, it is expected that taking account of macroscale fluctuations of the extinction coefficient inside an individual cloud will not lead to substantial changes in radiative properties of the cumulus field.

The calculations of $\frac{\partial\langle R\rangle}{\partial N}$ in cumulus differ essentially from those in stratus, because in the former case when estimating $\frac{\partial\langle R\rangle}{\partial N}$ one must specify not only the optical characteristics, most important at small N, and solar zenith angle, but also the initial value of cloud fraction about which the cloud amount will vary. Mean cloud amount and its variations depend on geographic location; therefore, to estimate correctly the derivative of the mean albedo with respect to the cloud amount, it is necessary to take into consideration the spatiotemporal variation of the global cloud field.

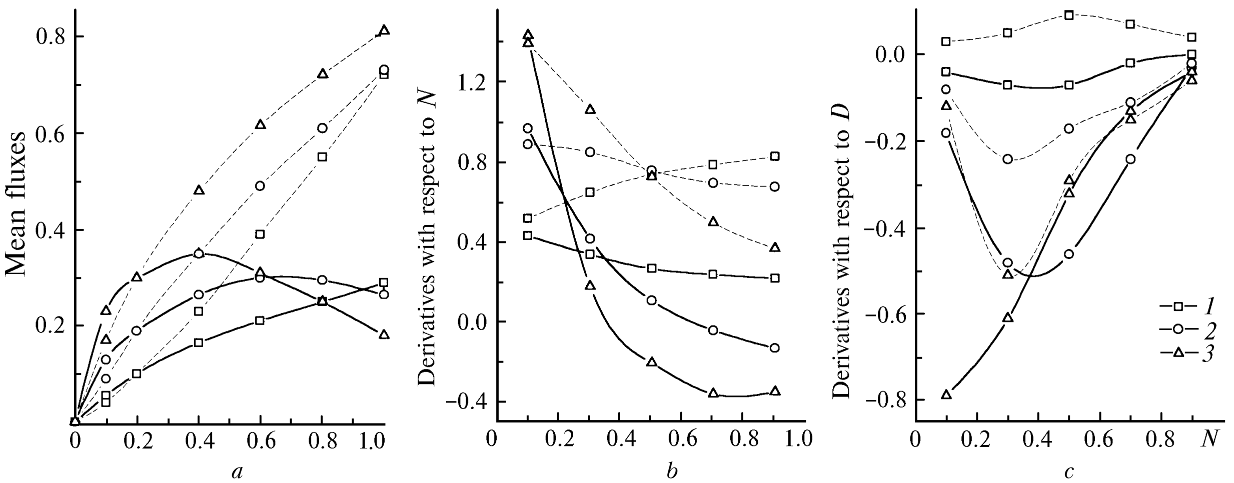


FIG. 4. The influence of solar zenith angle on the mean fluxes (a), their partial derivatives with respect to cloud fraction (b), and cloud horizontal size (c) for $\sigma = 60$ km^{-1}, $H = 0.5$ km, *and* $D = 0.25$ km; *here* $\xi_\otimes = 0$ (*1*), 30 (*2*), *and* 60°(*3*)*; solid lines show transmission and dashed lines correspond to reflection.*

Radiation modules of GCMs calculate spectral and integral fluxes of upwelling and downwelling solar and long–wave radiation at different altitudes in the atmosphere. In calculation of the mean spectral fluxes in the near–IR spectral range it is necessary to consider not only the scattering and absorption by atmospheric aerosol and reflection from the underlying surface, but also the absorption by atmospheric gases, primarily by water vapor, carbon dioxide, and ozone.

The vertical profiles of upward and downward fluxes of short–wave radiation modulated by broken clouds were first investigated in Refs. 39–41, where one can find a description of the models of meteorological parameters, optical properties of aerosol, vertical profiles of H_2O, CO_2, and their transmission functions as well as the algorithms of calculations.

Figure 5 presents the mean spectral radiative characteristics calculated for two values of albedo A_s of a Lambertian surface. The value $A_s = 0$ roughly represents the albedo of ocean and $A_s = 0.8$ is the albedo of snow cover. At $\xi_\otimes = 0°$ and $A_s = 0$ the aerosol–radiation interaction and gaseous absorption have little effect on qualitative result: the mean downward flux of diffuse radiation at cloud top is larger while the mean upward flux at cloud base is smaller in cumulus than in equivalent stratus (Figs. 5*a* and *b*, curves *1* and *3*). Radiation leaving the cumulus cloud through sides undergoes, on average, fewer scattering events than radiation exiting through the cloud top and base. For this reason, the diffuse radiation is, on the average, less absorbed in cumulus than in equivalent stratus (Fig. 5*c*, curves *1* and *3*). At the centers of strong absorption bands of H_2O and CO_2, the incident radiation is absorbed almost totally, so that the mean fluxes and the absorption, by a cloud layer, of diffuse radiation are both negligible.

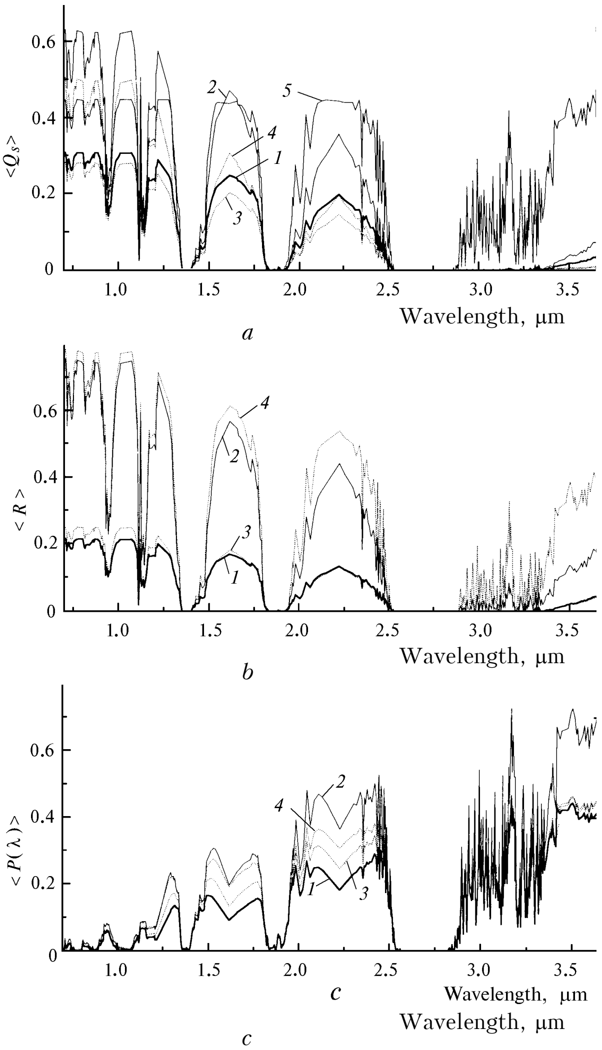


FIG. 5. The mean spectral fluxes of downwelling radiation at the cloud bottom $\langle Q_s \rangle$ *(a) and upwelling radiation at the cloud top* $\langle R \rangle$ *(b) as well as the mean spectral cloud absorption of scattered radiation* $\langle P \rangle$ *(c) for* $\xi_\otimes = 0°$, $\sigma = 30$ km^{-1}, $N = 0.5$ km, *and* $D = 0.25$ km: *cumulus (1 and 2) and stratus (3 and 4); the underlying surface albedo* $A_s = 0$ *(1 and 3),* $A_s = 0.8$ *(3 and 4), and the mean direct radiation flux at the underlying surface level (5).*

At $A_s = 0.8$ the underlying surface reflects the major portion of incident flux of total radiation. This radiation, having interacted with the under–cloud layer, can be treated as a diffuse source illuminating the lower cloud boundary and can yield a significant increase in the mean fluxes under consideration (Figs. 5*a* and *b*, curves *1*, *2* and *3*, *4*). The diffuse radiation in the presence of a sufficiently well reflecting surface is, on the average, more strongly absorbed in cumulus (Fig. 5*c*, curves *2* and *4*). This is because in cumulus the surface–reflected radiation may interact not only with cloud bases, but with numerous cumulus sides as well. The fraction of direct radiation passing through the cloud gaps is smaller in cumulus, hence, the reverse is true for diffuse fraction. Cloud particles absorb radiation in each interaction, thus validating the inequality $\langle P \rangle > \langle P_{St} \rangle$.

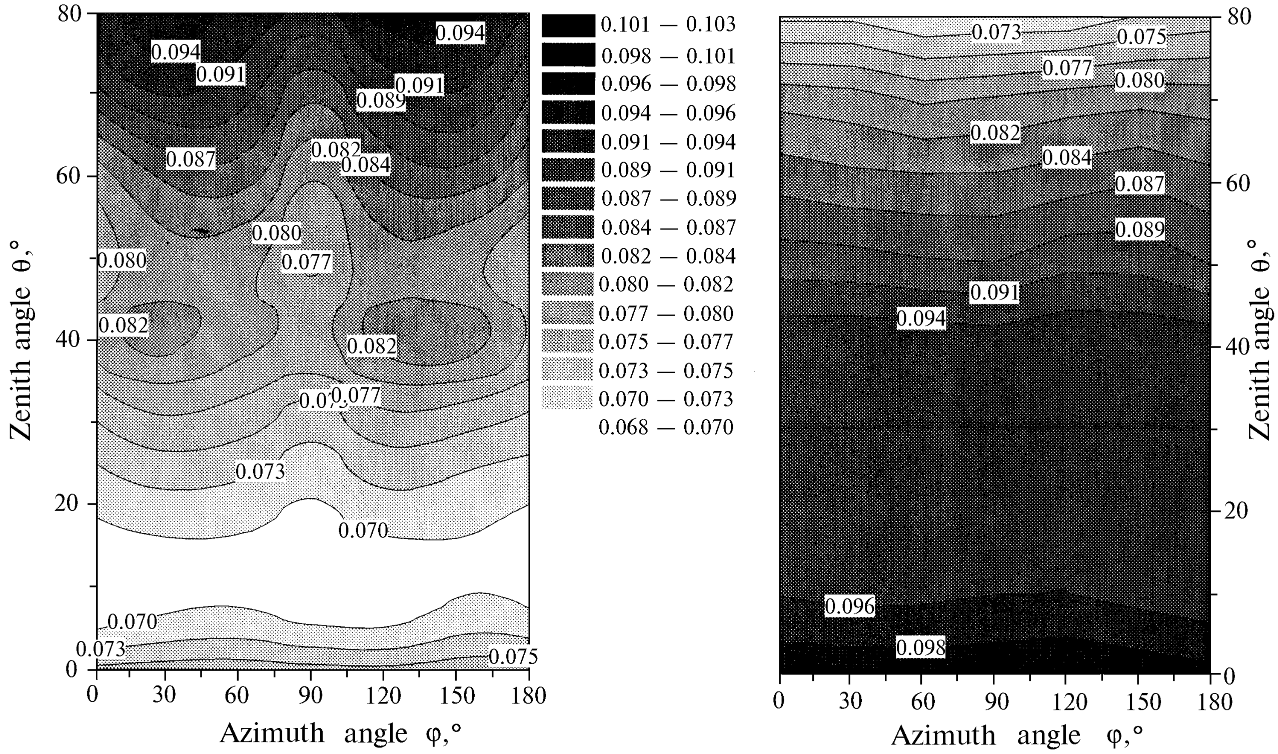
The results presented above clearly illustrate the importance of the effects of stochastic geometry of cumulus to radiative transfer. Due to these effects the mean radiative characteristics of cumulus differ (by tens of percent) from the corresponding characteristics of equivalent stratus either of individual effective cloud or an ensemble of identical clouds regularly located in space. The mean albedo of stratus with inhomogeneous internal structure[6,42,43] and with random upper boundary[44] is also substantially different from the albedo of a plane–parallel layer of a mean optical depth. These differences must be accounted for in radiation moduli of GCMs which need to be refined through the use of more realistic models of cloud–radiation interaction.

5. BRIGHTNESS FIELDS OF BROKEN CLOUDS

Global monitoring of optically active components of the atmosphere and underlying surface affords a variety of facilities, most powerful of which are the methods and means of remote optical sensing[45–47] permitting continuous observations of the dynamics of meteorological fields, the spatiotemporal variations of greenhouse–gas concentration, optical properties of aerosol, and micro– and macroparameters of clouds and underlying surface. In this context, the most promising is the use of the corresponding spacecraft–borne complex allowing one to obtain the information on optical–meteorological and radiation fields over large areas of the Earth over short periods during which the atmosphere changes insufficiently.

The methods of interpreting the data of satellite measurements on outgoing radiation are based on the solution of the transfer equation establishing the relationship between the characteristics of radiation recorded by a receiver and the parameters of the atmosphere–underlying surface system. Almost all existing techniques for retrieving the system parameters from outgoing short–wave and long–wave radiation measurements use the solution of transfer equation in a homogeneous plane–parallel cloud layer. The random geometry of broken clouds may have an appreciable effect on brightness fields, thus introducing a major uncertainty in the solution of inverse problems of remote sensing.

The statistical characteristics of brightness fields of visible solar radiation in broken clouds were considered in Refs. 48–52. As an example, Fig. 6 gives the mean intensity of reflected radiation as a function of zenith and azimuth observation angles θ and φ (Ref. 52). The calculations use the model of cumulus field generated by the Poisson point fluxes on straight lines. Such a cloud field is statistically homogeneous and nonisotropic, and the cloud bases are squares, on the average. The latter fact implies that the cloud optical characteristics in horizontal plane possess, on the average, the mirror symmetry about the straight line passing through an arbitrary point in azimuth direction $\varphi = 0$, $\pm\, 45$, and 90°. Obviously, at $\xi_\otimes = 0°$ the mean intensity in cumulus $\langle I_{Cu} \rangle$ will itself possess the same symmetry (Fig. 6*a*). As could be expected, the mean intensity in equivalent stratus $\langle I_{St} \rangle$ is independent of the azimuth angle of observation φ (Fig. 6*b*); slight differences are caused by computational errors. It is seen that $\langle I_{St} \rangle$ is maximum at $\theta \sim 0°$ and decreases with increasing θ, with inverse behavior for cumulus. This means that $\langle I_{St} \rangle$ and $\langle I_{Cu} \rangle$ qualitatively may behave differently as functions of zenith angle. Generally speaking, both cumulus and stratus are non–Lambertian reflectors.



a *b*

FIG. 6. The mean intensity of reflected solar radiation for $\xi_\otimes = 0°$, $N = 0.5$ km, $\sigma = 30$ km^{-1}, $H = 0.5$ km, and $A_s = 0$; *cumulus* ($\gamma = D/H = 1$) *(a) and stratus* ($\gamma = 0$) *(b).*

Let us discuss briefly the effect of differences between the brightness fields of cumulus, equivalent stratus, and Lambertian–reflecting clouds on the accuracy of retrieving the mean albedo of cumulus cloudiness. Let a nadir–looking receiver located on a satellite have the field of view angle $\alpha < \pi/2$. Obviously, this receiver can measure not the mean albedo $\langle R \rangle$, but rather the integral $\langle F_{mes} \rangle$ of the mean intensity $\langle I^{\uparrow}(\vartheta, \varphi) \rangle$ of radiation outgoing through the atmospheric top over the solid angle of the receiver field of view

$$\langle R \rangle = \int_0^{2\pi} d\varphi \int_0^1 \langle I^{\uparrow}(\upsilon, \varphi) \rangle \upsilon \, d\upsilon \, ,$$

$$\langle F_{mes} \rangle = \int_0^{2\pi} d\varphi \int_{\cos\alpha}^1 \langle I^{\uparrow}(\upsilon, \varphi) \rangle \upsilon \, d\upsilon, \qquad (6)$$

where $\upsilon = \cos\theta$. The problem is to establish the unique relationship between $\langle F_{mes} \rangle$ and $\langle R \rangle$, which is solved using angular distributions of intensity obtained for equivalent stratus or "Lambertian" cloud (see, e.g., Ref. 53). We introduce the notation

$$\delta = \frac{\langle R \rangle - \langle R_j \rangle}{\langle R \rangle} \times 100\% \, , \qquad (7)$$

where $\langle R_j \rangle$ is the mean albedo of cumulus field reconstructed using the angular distributions of stratus (index j = St) or "Lambertian" (index j = Lam) clouds. By definition, δ gives the error in determination of the mean albedo of cumulus caused by neglecting the effects of stochastic cloud–field geometry on radiative transfer; its values are given in Fig. 7 (Ref. 49). It is seen that the assumption of Lambertian properties of cumulus leads to either overestimation or underestimation of the values of the mean albedo, while the use of the angular distributions of stratus systematically overestimates the mean albedo, with values of δ as large as ~ 10–20%.

We have considered, so far, the mean fluxes and fields of solar–radiation brightness in cloud fields of random geometry. No less significant component of the Earth's radiation regime than the mean fluxes is the long–wave fluxes coming from the atmosphere and underlying surface. Knowledge of the brightness fields of long–wave radiation is required for solving of many important problems, e.g., for correct evaluation of disturbing effect of cloud cover in the problem of optical sounding of oceanic surface temperature from space. The equations for intensity moments of long–wave radiation and the methods of solution can be found in Refs. 54–57, where also studied are the multiple–scattering effects and the differences between the brightness temperatures of cumulus and equivalent stratus. It has been shown that the multiple scattering is only negligible for optically dense cumulus of optical thickness $\tau > 15–20$ and zenith viewing angles $\theta < 60–70°$. With these τ and θ values, the error in the determination of brightness temperature due to the neglect of scattering effects does not exceeds 1 K. The brightness temperature difference $\delta T = T_{St} - T_{Cu}$ between equivalent stratus (T_{St}) and cumulus (T_{Cu}) is a function of cloud–field parameters and viewing angle and varies from – 5 (near zenith) to 15 K (near horizon). Thus, the effects caused by the stochastic geometry of cumulus can substantially influence both the short–wave and long–wave radiative transfer. This should be kept in mind when calculating the long–wave radiative fluxes, when estimating the parameter of climate sensitivity as well as when interpreting the remote sensing data on parameters of the atmosphere and underlying surface in the long–wave spectral range.

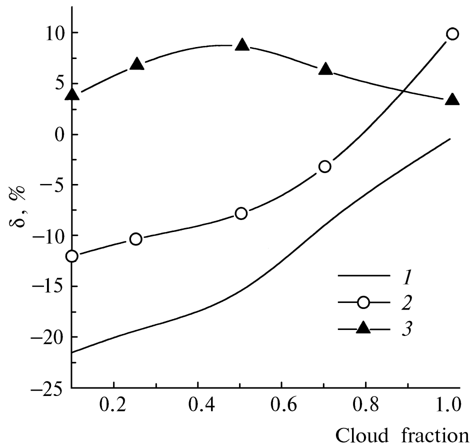


FIG. 7. Values of δ *for* $\xi_{\otimes} = 0°$, $\sigma = 30$ km^{-1}, *and* $D = H = 0.5$ km: *stratus (1) and "Lambertian" clouds (2 and 3); the underlying surface albedo* $A_s = 0$ *(1 and 2) and* $A_s = 0.8$ *(3).*

5. CONCLUSION

The radiative transfer theory in broken clouds has been intensively developed during recent years. New models, taking into account the stochastic geometry of broken clouds, have been created and the existing ones have been improved. Further impetus is gained by the methods of solving the equations for intensity moments by Monte Carlo method. Our understanding of the impact of the stochastic cloud geometry on radiative transfer is substantially increased. Numerous calculations made using different broken–cloud models show the results differing by tens percent from calculations using the models of a plane–parallel layer, separate cloud, and cloud ensemble with a regular spatial arrangement. These disagreements are too pronounced to be ignored in the models of weather and climate. The radiation moduli of GCMs need to be improved by employing, in place of plane–parallel models, more realistic models of interaction between stochastic clouds and radiation.

Despite the achievements, some uncertainties remain in modeling the radiative transfer in broken clouds. The analysis of satellite images of cloud cover provides a valuable information on cloud geometry projected onto some plane, nevertheless, giving little information on random geometry of stratus tops and bottoms ($H/D < 1$) and on three–dimensional geometry of cumulus ($H/D \sim 1$). Air– and spaceborne lidars offer good promises for this purpose.

The statistical characteristics of fluxes and brightness fields in statistically homogeneous broken clouds can be calculated using both the numerical simulation of cloud and radiation fields, and the equations for intensity moments. The use of these equations considerably increases the efficiency of Monte Carlo algorithms, for example, for computation of the statistical characteristics of intensity in a given direction or variance and correlation function of solar radiation fluxes. These equations can be solved not only by the Monte Carlo method, but also using other numerical and approximate techniques, that may be of utility in developing the GCM radiation codes. Real clouds are not statistically homogeneous thus requiring the generalization of equations for intensity moments to this case.

The radiation models of broken clouds will be tested and improved as the data of complex radiation experiments are available, among whose are the measurements, on agreed spatiotemporal scales, of all parameters of the atmosphere––underlying surface system governing the radiative transfer, integral and spectral fluxes of upwelling and downwelling short–wave and long–wave radiation as well as brightness fields at different spectral intervals.

ACKNOWLEDGMENTS

This study has been done under financial support from Pacific Northwest Laboratories (DOE's ARM Program, Contract No. 350114–A–Q1).

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