SOLAR RADIATIVE TRANSFER IN THREE-DIMENSIONAL STRATOCUMULUS CLOUDS: THE EFFECT OF VERTICAL INHOMOGENEITY

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Solar radiative transfer in 3D broken stratocumulus clouds is considered. A 3D cloud model with explicit microphysics (Oklahoma, USA) and the Monte Carlo method are used to study the influence of vertical variability of the extinction coefficient σ on the radiative characteristics of stratocumulus clouds. It is shown that vertical cloud inhomogeneity can decrease the area-mean albedo by approximately 10%. *Irregular cloud geometry has stronger influence on the mean albedo and transmittance than inhomogeneous internal cloud structure. The mean radiative flux is more sensitive to variations of the vertical profile of the variation coefficient $VC(\sigma)$ than to those of the vertical profile of the mean $\langle\sigma\rangle$. Two-dimensional fields of albedo, transmittance, and horizontal transport depend strongly on the vertical stratification of clouds.*

1. INTRODUCTION

Numerous issues of the climate prediction and dynamics, the problems in cloud formation studies and remote sensing cannot be resolved successfully without correct accounting for cloud-radiation interaction. In order to describe adequately the relationship between cloud radiative properties and cloud optical and geometrical characteristics, one must use cloud models, that correctly account for the spatial (temporal) fluctuations of cloud parameters, as well as appropriate radiation calculation techniques.

Based on the ground-based and space observations, lognormal[1] and gamma[2] distributions were proposed for approximation of *horizontal* distribution of the optical depth τ of marine *Sc* clouds. These distributions, as well as the assumption of plane-parallel cloud layer, have been widely used for investigation of the influence of horizontal inhomogeneity of τ on radiative transport in *Sc* clouds, as well as on the accuracy of retrieval of their optical characteristics.[3–8] It is shown that the mean albedo is less sensitive to $\langle\tau\rangle$ than to τ distribution characteristics and that the horizontal inhomogeneity of τ may reduce the mean albedo by approximately 15%. Obviously, only *horizontal* variability of cloud fields can be investigated by means of the ground and satellite observations.

The inhomogeneity of real stratocumulus clouds is caused by both the horizontal and *vertical* variations of optical and geometrical cloud characteristics. Usually, the vertical profiles of cloud microphysical/optical parameters are determined from airborne measurements,[9,10] while lidar sensing data may be successfully used to study irregular geometry of the cloud top and bottom boundaries with high spatial resolution.[11,12] Strong variability of cloud properties, as well as limited possibility of their measurements, prohibits the acquisition of detailed and *simultaneous* information on the vertical and horizontal structure of a cloud. For this reason, specialists in the 3D-cloud modeling have to resort to assumption of *independence* of the vertical and horizontal variations of the cloud parameters and on some assumptions concerning vertical stratification of the cloud optical parameters. For instance, the vertical behavior of the mean extinction coefficient $\langle\sigma\rangle$ can be estimated either by some typical vertical profile of the effective radius and liquid water content[13] or by the mean vertical profile of $\langle\sigma\rangle$ that matches the adiabatic profile of the liquid water content in the cloud field.[14]

To construct cloud models, which adequately treat the vertical structure and horizontal variability of clouds, and to create improved radiation transfer parameterizations, the following questions should be addressed:

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– How strongly does the vertical stratification of 3D clouds influence their radiation parameters?

– What factors characterizing the vertical cloud inhomogeneity are most important?

Because the vertical and horizontal variations of cloud optical/geometrical parameters are *interrelated*, in answering these questions this relationship should be accounted for adequately. Three-dimensional cloud scale models (e.g., see Refs. 15 and 16), which may provide a detailed information on the vertical and horizontal variability of cloud field, seem to be most promising in this regard. Using these models, the dependence of cloud radiative properties on the structure of a cloud field can be thoroughly studied. For instance, a 3D cloud scale model (Colorado, USA) was used to estimate the inhomogeneity effect of unbroken *Sc* clouds on the mean broadband albedo.[15] It was demonstrated that the latter strongly depends on the horizontal variability of a cloud layer, and that result was generally consistent with the monochromatic findings.[3]

The primary goal of this paper was to explore the effect of vertical variability of the extinction coefficient of 3D broken *Sc* clouds on the mean and 2D fields of albedo, transmittance and horizontal transport based on the 3D cloud scale model developed at the Cooperative Institute for Mesoscale Meteorological Studies (Oklahoma, USA).[16,17]

The paper consists of four sections. Section 2 presents optical parameters, as well as the cloud models and solution technique. Sensitivity of the mean, variation coefficient, and horizontal distribution of the radiative fluxes to vertical structure of the extinction coefficient is discussed in Section 3. Section 4 summarizes the main results obtained.

2. APPROACH

We use the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) Large Eddy Simulation (LES) cloud model that combines the 3D dynamics with explicit formulation of the liquid phase microphysical processes. Cloud physics processes are treated explicitly based on the prediction equations for cloud particle spectra.[17] The spectra of the basic cloud particles are taken into consideration. Among those there are condensation nuclei (19 categories), cloud and rain drops (25 categories). The equations for particle size-distribution functions include processes of advection, sedimentation, turbulent mixing, and individual microphysical processes of nucleation, condensation (evaporation), and stochastic coagulation. The evolution of dynamical fields takes into account both the long-wave and short-wave radiation processes that are calculated interactively at each time step based on the explicitly predicted drop spectra. The model has been extensively validated against observations from the Atlantic Stratocumulus Experiment (ASTEX), Monterey Area Ship Experiment (MAST), and some other cases.

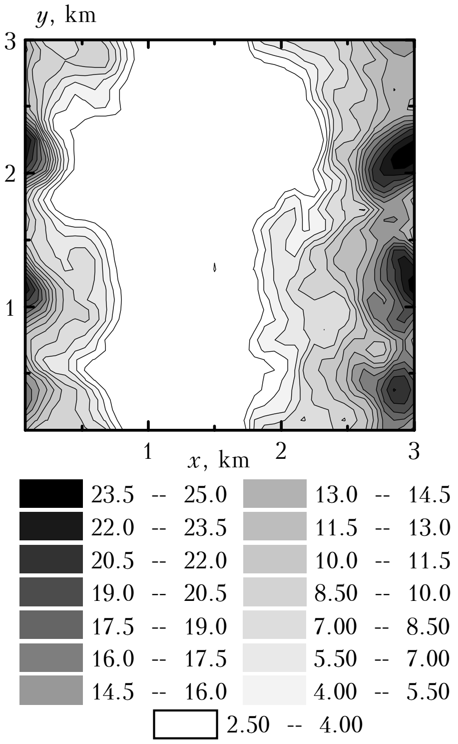
We simulated low-level broken *Sc* clouds observed during the ASTEX field program. The strong capping temperature inversion resulted in a fairly uniform cloud top; however, because of heterogeneous distribution of the surface fluxes and the presence of drizzle in the turbulent boundary layer, the cloud base boundary varied very strongly. The integration domain consisted of 40×40×51 grid points with the horizontal and vertical resolution of 0.075 km and 0.025 km, respectively.

In calculations of radiation characteristics we used the Monte Carlo method and periodic boundary conditions. To make the computations less time-consuming, the method of maximum cross section[18] was employed. For each pixel, we calculated the upward, downward, and horizontal fluxes of solar radiation assuming the solar zenith angle of 60°. The azimuth solar angle measured from *OX* axis was set to be zero throughout the computation. It was assumed that a unit parallel solar flux is incident on the top of the cloud layer. Impact of the aerosol atmosphere and underlying surface was not considered. With 120 million photons used in calculations, the computational error is estimated to be less than 1%.

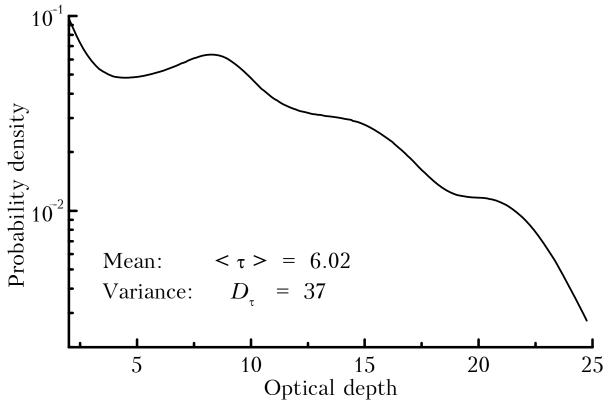
A. Cloud optical characteristics

In each cell (pixel) we used the Mie theory[19] for the 0.69 μm wavelength to calculate the cloud optical parameters within it: the extinction coefficient σ and the scattering phase function. In the calculations, we used data on the complex refractive index from Ref. 20.

For calculating the radiative characteristics, we need information on cloud field geometry and, in particular, on the heights of cloud top Ht and bottom Hb boundaries. In other words, we have to define a criterion for unambiguous identification of whether a given pixel belongs to a cloud or to the cloud-free atmosphere. Presently, there are no clear quantitative definitions for "cloudB and "cloud boundaries.B Here, we used as a criterion the threshold of 3 km^{-1}, i.e. pixels with $\sigma > 3$ km^{-1} were classified as cloudy. Note that values of σ between 2.5 and 250 km^{-1} have been measured with the accuracy better than 20% (Ref. 21). We took as a height of the cloud top (bottom) boundary the highest (lowest) height in the cloud. According to the criterion chosen ($\sigma > 3$ km^{-1}) and the way of identifying the cloud boundaries, the heights of cloud top and bottom boundaries were 0.775 km and 0.15 km, respectively. The 2D horizontal distribution and the one-point probability density of τ are shown in Fig. 1. Note that the parameters of τ distribution of the modeled cloud field well agree with the parameters of τ distribution (scene B13) inferred from satellite observations.[2]



a



b

FIG. 1. Two-dimensional field (a) and probability density (b) of the optical depth.

B. Cloud models

Usually, the radiative properties of the 3D clouds are studied using only mean vertical profile of <σ> (see, for example, Refs. 13 and 14). However, it is well known that the cloud radiative properties depend nonlinearly on its optical and geometrical parameters. This necessitates a detailed study of the sensitivity of cloud radiative properties to the statistical characteristics of the vertical profile of σ and to the cloud geometrical structure. Note that the information on the vertical profiles of the mean <σ> and variation coefficient $VC(\sigma)$ can be obtained from airborne measurements.[19] To estimate the influence of <σ>, $VC(\sigma)$, and irregular geometry of *Sc* clouds on their radiative characteristics, the following four cloud cases have been considered:

The first (3*D*) case has irregular geometry and inhomogeneous internal structure. The extinction coefficient σ_{3D} varies in horizontal and vertical directions. The cloud optical depth $\tau(x, y)$ is calculated by integrating $\sigma_{3D}(x, y)$ in the vertical.

The second (2*D*) case is a plane-parallel horizontally inhomogeneous cloud layer. The extinction coefficient σ_{2D} varies only in horizontal direction, while in each vertical column its value is $\sigma_{2D}(x, y) = \tau(x, y)/\Delta H$.

The third (2*Dmv*) case consists of two plane-parallel horizontally inhomogeneous layers. The top (TOP) and bottom (BTM) layers have nearly the same mean optical depth, i.e., $\langle\tau^{\mathrm{TOP}}_{2Dmv}\rangle \approx \langle\tau^{\mathrm{BTM}}_{2Dmv}\rangle \approx \langle\tau\rangle/2$ and $\langle\tau^{\mathrm{TOP}}_{2Dmv}\rangle + \langle\tau^{\mathrm{BTM}}_{2Dmv}\rangle = \langle\tau\rangle$. The extinction coefficient for the two layers was calculated from the following formulas:

$$\sigma^{\mathrm{TOP}}_{2Dmv}(x, y) = \tau^{\mathrm{TOP}}_{2Dmv}(x, y)/\Delta H_{\mathrm{TOP}},$$

$$\sigma^{\mathrm{BTM}}_{2Dmv}(x, y) = \tau^{\mathrm{BTM}}_{2Dmv}(x, y)/\Delta H_{\mathrm{BTM}}, \qquad (1)$$

where ΔH_{TOP} and ΔH_{BTM} are the geometrical thicknesses of the top and bottom layers, respectively.

The fourth (2*Dm*) case differs from the 2*Dmv* case only in the way of calculating the extinction coefficient in the top and bottom layers:

$$\sigma^{\mathrm{TOP}}_{2Dmv}(x, y) = \sigma_{2D}(x, y)\,\langle\sigma^{\mathrm{TOP}}_{2Dmv}\rangle/\langle\sigma_{2D}\rangle,$$

$$\sigma^{\mathrm{BTM}}_{2Dmv}(x, y) = \sigma_{2D}(x, y)\,\langle\sigma^{\mathrm{BTM}}_{2Dmv}\rangle/\langle\sigma_{2D}\rangle. \qquad (2)$$

Figure 2 presents vertical profiles of the mean <σ> and variation coefficient $VC(\sigma)$, corresponding to these cases. The 2*D* and 2*Dm* cases differ only in the vertical profile of <σ>. The 2*Dm* and 2*Dmv* cases have the same vertical stratification of <σ>, but different vertical profiles of $VC(\sigma)$. It is significant to note that the 3*D*, 2*D*, 2*Dmv*, and 2*Dm* cases have identical two-dimensional fields of optical depth $\tau(x, y)$ and, hence, the probability distribution function $p(\tau)$ (Fig. 1).

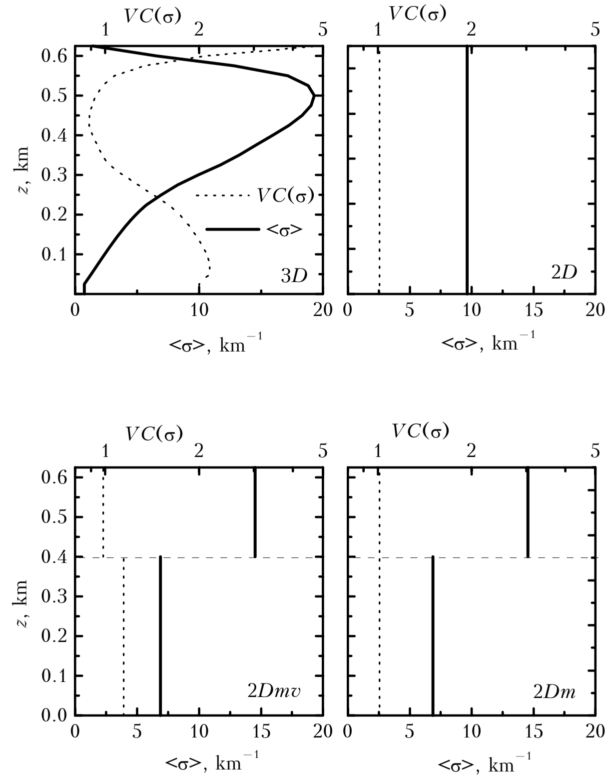


FIG. 2. Vertical profiles of the mean <σ> and variation coefficient VC(σ) of the extinction coefficient corresponding to different cloud cases.

3. RADIATIVE PROPERTIES OF *Sc* CLOUDS

A. Mean fluxes

The Independent Pixel Approximation (IPA) is widely used to calculate the area-mean albedo <*R*> (Refs. 3–5). In essence, IPA considers the radiative properties of each pixel to be the functions of only its vertical optical depth τ. The mean cloud albedo <*R*> can be approximated by integrating $R_{pp}(\tau)p(\tau)$ over all τ, where $R_{pp}(\tau)$ is the albedo of a plane-parallel homogeneous layer with the optical depth τ, and $p(\tau)$ is the probability distribution function. This approximation calculates quite accurately the mean albedo of the *overcast Sc*.[3,4] It has also been found that, for the overcast *Sc*, the vertical inhomogeneity of σ has little influence on the mean albedo.[15,22,23] Will this finding also hold for the *broken Sc*? In other words, given two broken *Sc* cloud fields with the same $p(\tau)$ but different vertical stratifications of the extinction coefficient, what will be the difference between their mean albedos?

As an illustration of the effects caused by the vertical cloud inhomogeneity, Figure 3 presents realizations of cloud fields with the same field of τ but different vertical structures. As clearly seen from the figure, in vertically inhomogeneous clouds a considerable portion of radiation may propagate in gaps between the clouds, as well as through optically thin cloud edges. Therefore, it can be expected that the vertically inhomogeneous clouds will be more transparent to the solar radiation than their vertically homogeneous counterparts.

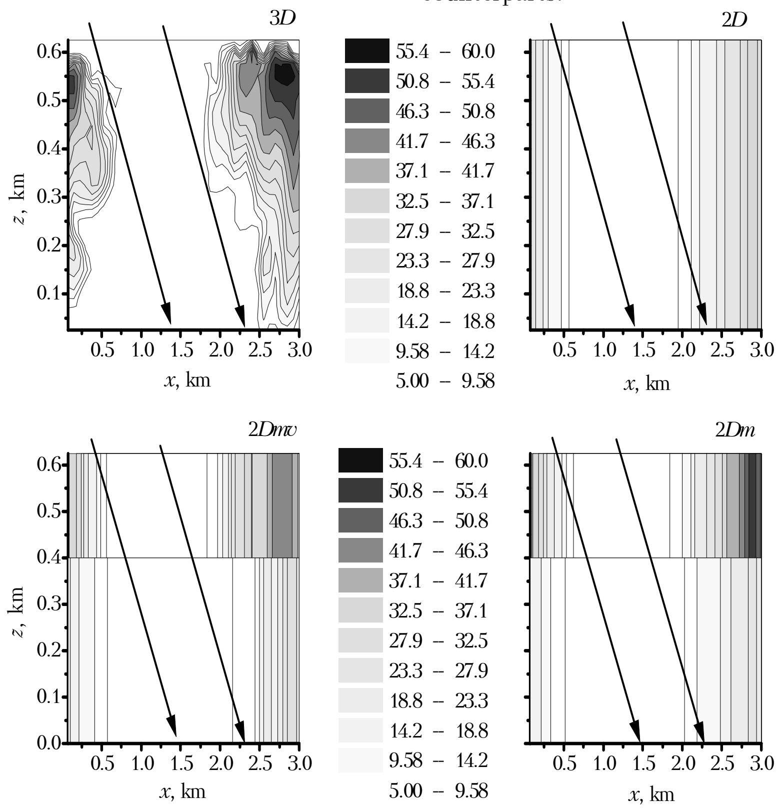


FIG. 3. Vertical cross sections (y = 0.05 km) of cloud field realizations corresponding to different cloud cases. Arrows show the direction of solar radiation propagation.

To quantify the sensitivity of the mean albedo $<R>$ and the transmittance $<T>$ to the three factors: (1) the mean vertical profile of $<\sigma>$, (2) vertical profile of variation coefficient $VC(\sigma)$, and (3) irregular cloud geometry, we will consider three indices

$$\delta F_m = 100\% \{<F_{2D}> - <F_{2Dm}>\}/<F_{2D}>,$$
$$\delta F_{m,VC} = 100\% \{<F_{2D}> - <F_{2Dmv}>\}/<F_{2D}>, \quad (3)$$
$$\delta F_{m,VC,IG} = 100\% \{<F_{2D}> - <F_{3D}>\}/<F_{2D}>,$$

where $<F>$ denotes $<R>$ or $<T>$. The indices δF_m, $\delta F_{m,VC}$, and $\delta F_{m,VC,IG}$, respectively, characterize only the effect of the vertical profile of $<\sigma>$, the joint effect of the vertical profiles of $<\sigma>$ and $VC(\sigma)$, and the overall effect of internal inhomogeneity and irregular geometry.

These indices are presented in Fig. 4, where we see that the vertical profile of $<\sigma>$ has little influence on the mean fluxes. This agrees well with the result obtained earlier for a cloud field as regularly spaced clouds of the same extent.[13] If compared with the mean $<\sigma>$, the variation coefficient $VC(\sigma)$ varies weakly with altitude (Fig. 2); however, the value of $\delta R_{m,VC}$ is nearly three times larger than that of δR_m (Fig. 4).

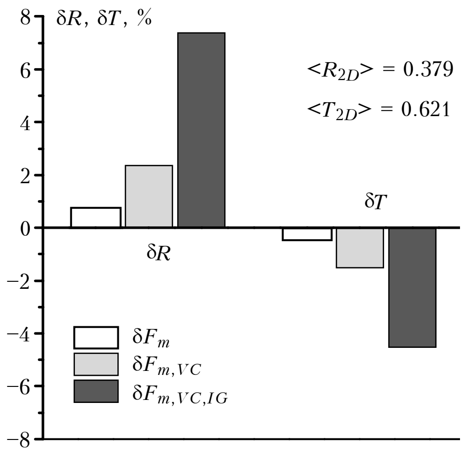


FIG. 4. Relative deviations of the mean albedo δR and mean transmittance δT caused by inhomogeneous internal cloud structure and its irregular geometry.

Therefore, the mean albedo stronger depends on the vertical profile of $VC(\sigma)$; and this is also true for the transmittance. The obtained results suggest that the knowledge of the mean profile of σ is generally insufficient to estimate the mean fluxes correctly, and that more complete information concerning vertical cloud structure, at least in terms of the variation coefficient $VC(\sigma)$, is required. Also, the fact that $\delta F_{m,VC,IG}$ is more than three times larger than $\delta F_{m,VC}$ indicates that irregular cloud geometry has stronger influence on the solar radiation transfer than its inhomogeneous internal structure. This is consistent with the results obtained for simpler cloud models.[24,25] As a result of the overall impact of vertical cloud stratification, the mean albedo may decrease by approximately 10%. This should be accounted for in radiation parameterization in the case of broken clouds.

B. Horizontal transport

The importance of the *total* horizontal radiative transport inside the cloud layer between its top and bottom boundaries has been studied rather extensively.[7,24,26,27] Here we focus on the vertical profile of standard deviation $Sd(E)$ of the horizontal transport and the effect of the horizontal transport E on the variation coefficient of upward and downward fluxes.

The variance of horizontal transport is mostly determined by the irregular cloud geometry.[24] Recall (see Section 2) that Hb varies strongly, while Ht does not; so, $Sd(E)$ is maximum near the bottom boundary of a cloud layer (Fig. 5*a*). Unlike the irregular cloud geometry, the vertical profiles of $<\sigma>$ and $VC(\sigma)$ affect $Sd(E)$ most strongly in the top and middle parts of a cloud layer (Fig. 5*a*). The standard deviation $Sd(E)$ depends strongly on the vertical stratification of broken *Sc*: maximum difference between $Sd(E_{3D})$ and $Sd(E_{2D})$ is on the order of 200%. The inequality $Sd(E_{3D}) > Sd(E_{2D})$ holds for all vertical levels; and for the total horizontal transport the 2*D* and 3*D* values of $Sd(E)$ are 0.209 and 0.292, respectively. Therefore, the vertical cloud inhomogeneity may increase the variance of the total horizontal transport by approximately a factor of two.

How strongly does the horizontal transport influence the mean and variation coefficient of upward and downward going fluxes? To answer this question, we will compare the 3*D* calculations made with and without regard for horizontal transport. In the latter case, each pixel receives and looses radiation only through its top and bottom boundaries. This, in turn, leads to the situation, when the radiative transport is no longer influenced by (1) the effects caused by finite horizontal size of pixels and (2) the effects due to impact of sideward neighboring pixels (screening, mutual shading, and radiative interaction).[28–30] These effects are considered to be responsible for qualitative and quantitative differences in radiative properties between the cases with and without regard for E. Analysis of calculated results showed the mean vertical profiles of upward and downward going fluxes to depend weakly on the horizontal transport. However, E may have a considerable influence on their variation coefficients (Fig. 5*b*). For instance, the horizontal transport can increase the variation coefficient of the downward flux by approximately a factor of two (Fig. 5*b*). Since $Sd(E)$ is maximum near the cloud bottom, the effect of E on the variation coefficient of the fluxes is also the strongest in the bottom part of a cloud layer.

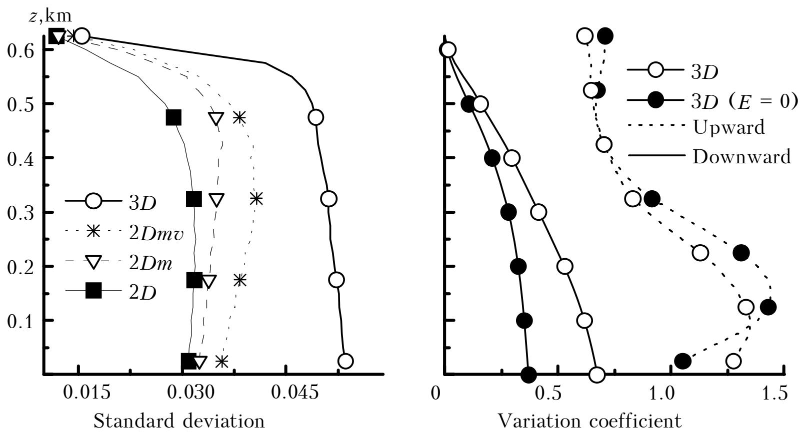


FIG. 5. Standard deviations of horizontal transport inside a cloud layer corresponding to different cloud cases (a) and vertical profiles of the variation coefficient of upward and downward going fluxes calculated with (open circles) and without (solid circles) regard for the horizontal transport (b).

C. Two-dimensional fields of albedo, transmittance, and horizontal transport

Now we consider the influence of vertical cloud inhomogeneity on the horizontal distributions of R, T, and total E. In the absence of absorption and horizontal transport ($E = 0$) there is a unique dependence between τ, on the one hand, and R and T, on the other hand,[31] i.e., the latter ones do not depend on the vertical stratification of σ. If the horizontal transport depends on the vertical variations of σ, the same do the albedo and transmittance. In the above discussion it was shown that the vertical profiles of $\langle\sigma\rangle$ and $VC(\sigma)$ and irregular geometry of broken Sc markedly influence $Sd(E)$ inside the cloud layer (Fig. 5a); therefore, the $2D$ field of total horizontal transport of E and, hence, the R and T fields also depend quite strongly on the above mentioned factors (Fig. 6).

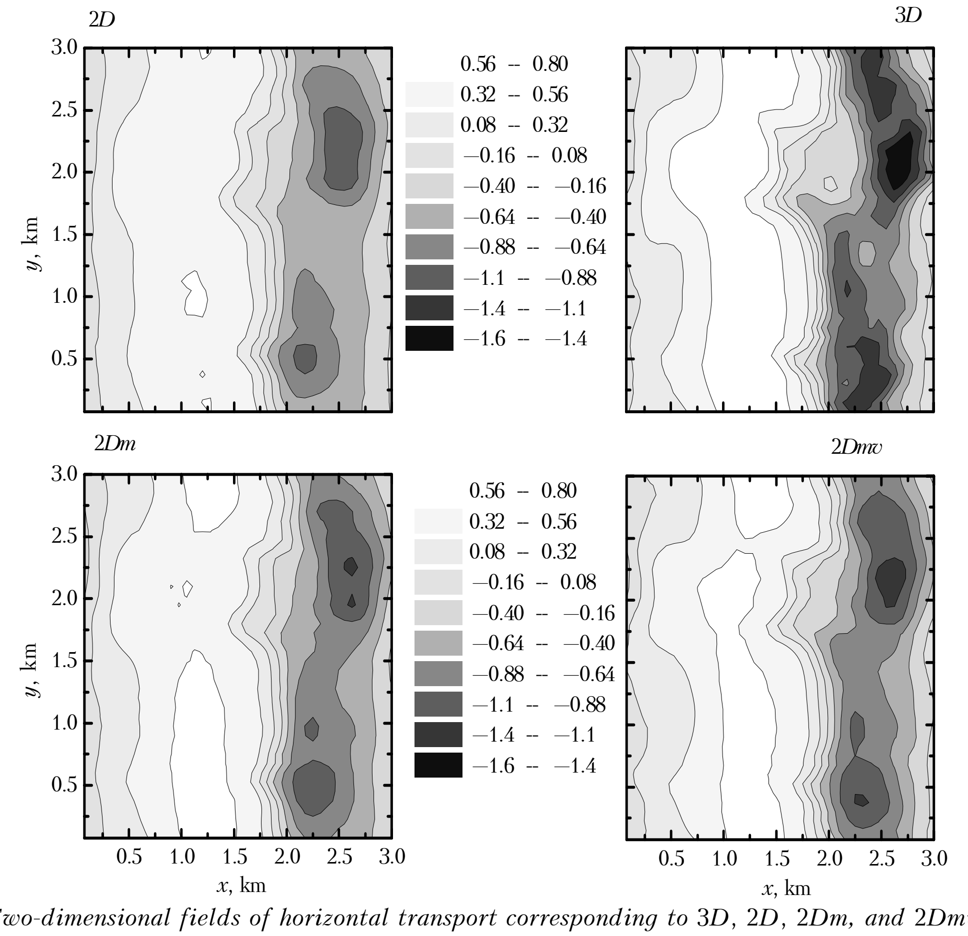


FIG. 6. Two-dimensional fields of horizontal transport corresponding to 3D, 2D, 2Dm, and 2Dmv cloud cases.

Small-scale (on the order of 0.05 km) measurements of albedo and transmittance are used in recent years for detailed studies of the horizontal variability of cloud optical depth[5,6] and absorption.[7,24,27,32] The neglect of horizontal transport seriously degrades an accuracy of retrieval of these characteristics. The spatial averaging of albedo and transmittance mitigates this effect. The averaging length depends not only on the mean and variance values, but also on the spatial structure of albedo, transmittance, and horizontal transport (see, e.g., Ref. 32). The calculated results clearly show that the vertical distribution of σ has a significant influence on 2*D* fields of *E*, *R*, and *T* (Figs. 6, 7, and 8).

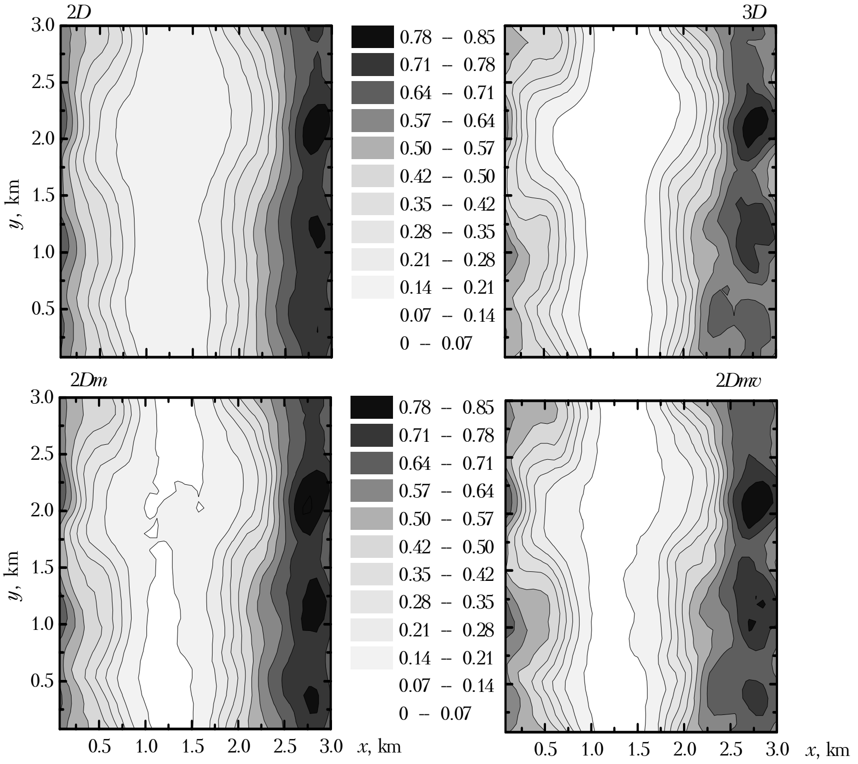


FIG. 7. Two-dimensional fields of albedo corresponding to the 3D, 2D, 2Dm, and 2Dmv cloud cases.

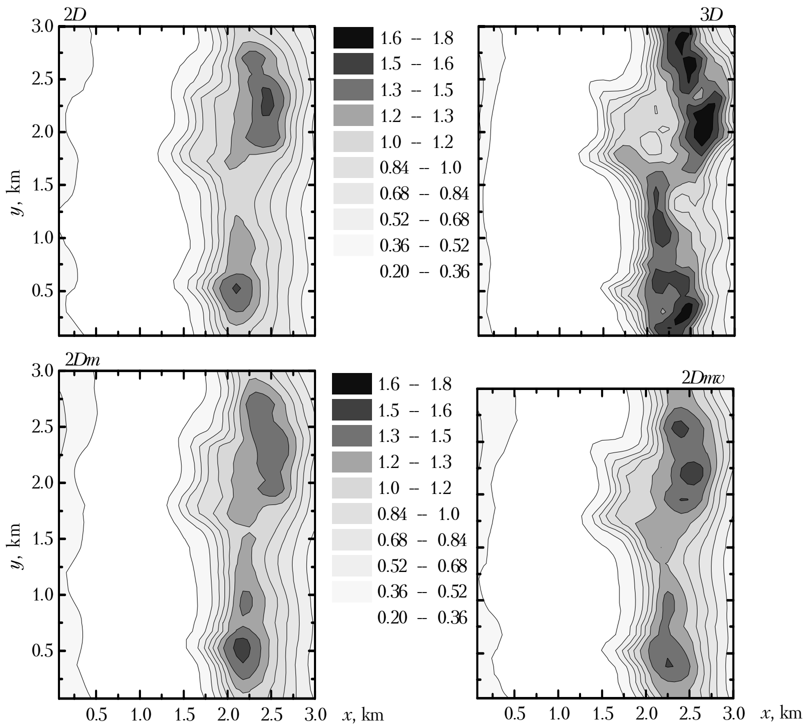


FIG. 8. Two-dimensional fields of the transmittance corresponding to the 3D, 2D, 2Dm, and 2Dmv cloud cases.

This fact should be taken into account when retrieving cloud parameters from space- and ground-based measurements. For instance, in the case of broken clouds, small-scale albedo measurements are widely used for retrieval of the cloud fraction generally defined as the ratio of the number of cloudy pixels to the total number of pixels. Separation into cloudy and non-cloudy pixels is made using a threshold albedo R_C. The pixels with the albedo exceeding R_C are interpreted as cloudy ones, while those with the albedo less than or equal to R_C are considered as clear-sky pixels.[33] Due to radiation effects, all clear-sky pixels in the $2D$ case and some of the clear-sky pixels in the $2Dm$, $2Dmv$, and $3D$ cases may have albedo values in excess of zero (Fig. 7). The neglect of the vertical cloud structure may thus lead to substantial errors in satellite-derived cloud fraction.

4. DISCUSSION AND SUMMARY

A 3D LES model of stratocumulus clouds with the explicit microphysics (CIMMS, Oklahoma) and the Monte Carlo method were used to study the influence of the vertical variability of the extinction coefficient σ of broken *Sc* clouds on the mean, variation coefficient VC, and horizontal distribution of upward, downward, and horizontal radiative fluxes in the visible spectral region. The main results obtained may be summarized as follows.

Many of the data available evidently show that a horizontally inhomogeneous layer with the mean optical depth $<\tau>$ has lower mean albedo than the plane-parallel homogeneous layer with the same $<\tau>$ (see, e.g., Ref. 3). The albedo difference may reach 15%. This paper shows that the vertical cloud inhomogeneity may *enhance* this difference by approximately 10%, because the stronger the cloud vertical inhomogeneity, the larger the fraction of radiation propagating in gaps between the clouds, as well as through optically thin cloud edges.

In practice, the information on the mean vertical profile of σ is, as a rule, used to study the radiative properties of $3D$ clouds. This paper shows that the mean albedo and the transmittance weakly depend on the vertical stratification of the mean extinction coefficient $<\sigma>$, while being more sensitive to the vertical profile of $VC(\sigma)$. In turn, the irregular cloud geometry has stronger influence on the mean albedo and transmittance than inhomogeneous internal cloud structure.

The Independent Pixel Approximation (IPA) is widely used to describe the radiation budget in inhomogeneous clouds. In particular, with this method the mean albedo of inhomogeneous overcast clouds can be calculated quite accurately, once the probability density function of the vertical optical depth $p(\tau)$ of clouds is known (see, e.g., Ref. 2). Here we have demonstrated that for reliable estimation of the mean albedo of *broken* stratocumulus, the information not only on $p(\tau)$, but also on the vertical structure of a cloud layer is needed.

The IPA neglects the horizontal radiative interaction between pixels. Our results suggest that within a cloud layer the horizontal radiative transport may be quite significant, and it may strongly depend on the vertical stratification of σ. Horizontal transport may have considerable influence on the variation coefficient of upward and downward going fluxes. Therefore, the inclusion of horizontal radiative transport in the thermodynamic equations of the cloud scale models is necessary to accurate account for cloud and boundary layer evolution.

The remote sensing techniques are aimed at determining cloud parameters by the measured radiation characteristics. For instance, small-scale (on the order of 0.05 km) albedo and transmittance measurements are used for detailed study of horizontal variability of the cloud optical depth and absorption. We have found that the vertical stratification of the extinction coefficient has considerable effect on the 2D fields of horizontal transport, albedo, and transmittance. Thus, when remotely sensed satellite data on broken clouds are interpreted neglecting vertical stratification of the cloud layer, retrieved cloud fraction may be overestimated.

The extinction coefficient varies insignificantly in the 0.7 –3.6 μm wavelength interval. Thus, the conclusions obtained in this paper for the visible region also hold true in the near IR range.

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