The Effect of Three-Dimensional Cloud Inhomogeneity on Shortwave Radiative Transfer

E. I. Kasyanov and Y. L. Kogan*
CIMMS, University of Oklahoma
Norman, Oklahoma
**On leave from the Institute of Atmospheric Optics,*
RAS, Tomsk, Russia

G. A. Titov
Pacific Northwest National Laboratory
Richland, Washington

Introduction

The effect of cloud inhomogeneity on radiative transfer in stratocumulus clouds, as well as retrieval of their optical properties, has been studied extensively during recent years. However, in many studies the clouds have been simulated by models that account only for horizontal inhomogeneity of liquid water path and, correspondingly, the optical depth (see Barker et al. 1996, Chambers et al. 1997, Davis et al. 1997, and Marshak et al. 1997).

In this paper, we explore the effects of three-dimensional inhomogeneity of the extinction coefficient on the shortwave radiative transport by numerically simulating clouds with a three-dimensional cloud model. We use the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) large eddy simulation (LES) cloud model that combines the three-dimensional dynamics with explicit formulation of liquid phase microphysical processes (Kogan et al. 1995). Cloud physics processes are treated explicitly based on the prediction equations for cloud particle spectra (Kogan 1991). The spectra of the basic cloud particles are taken into consideration: cloud condensation nuclei (19 categories), and 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 longwave and shortwave 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 other cases.

Approach

We simulated a marine low-level stratus layer observed during the ASTEX field program. The strong capping inversion resulted in a fairly uniform cloud top; however, the heterogeneous distribution of surface fluxes and drizzle in the turbulent boundary layer resulted in a highly variable cloud base. The integration domain consisted of 40 x 40 x 51 grid points with horizontal and vertical resolution of 0.075 km and 0.025 km, respectively. For each grid cell, the extinction coefficient and the scattering phase function were calculated based on Mie theory for the 0.69 µm wavelength from the predicted in the model drop size distributions. To evaluate the effect of spatial inhomogeneity, we compared two cases: the first is a fully three-dimensional case, C3D, with extinction coefficient, σ_{C3D}, varying both in the horizontal and in the vertical. Pixels with $\sigma_{C3D} < 3$ km^{-1} are assumed to be cloud-free, and according to this threshold, the cloud base and top height is Hb = 0.225 km and Ht = 0.775 km, correspondingly; hence, the cloud geometrical thickness is $\Delta H = 0.55$ km. The cloud optical depth $\tau(x,y)$ is calculated by integrating σ_{C3D} in the vertical.

The second case, C2D, has the same two-dimensional field of optical depth $\tau(x,y)$ as the C3D case, but is homogeneous in the vertical. This means that the extinction coefficient does not change in the vertical—in each vertical column, its value is equal to the mean value of the extinction coefficient for the corresponding column in the C3D case: $\sigma_{C2D}(x,y) = \tau(x,y)/\Delta H$. Evidently, the C3D and C2D cases have identical two-dimensional fields of optical depth $\tau(x,y)$. The vertical profiles of the mean value of the extinction coefficient, $\langle\sigma_{C3D}\rangle$, and its variation coefficient (ratio of standard deviation to the mean), $VC(\sigma_{C3D})$, are shown in Figure 1.

The cloud radiative properties were calculated by the Monte Carlo method. To single out the effect of the extinction coefficient, we assumed the same scattering phase function in both cases. The latter was calculated exactly for each grid cell in the C3D case and then its value, averaged over the whole domain, was used in calculations of radiative transfer. For each vertical column, we calculated the upward, downward, and horizontal radiative fluxes assuming the solar zenith angle of 60°. With 100 million photons used in calculations, the computational error is estimated to be less than 1%.

Results

We first consider the effect of cloud heterogeneity on upward (↑) and downward (↓) radiative fluxes by comparing the horizontally averaged mean values, $F^{\uparrow}$ and $F^{\downarrow}$, and variances, $Var(F^{\uparrow})$ and $Var(F^{\downarrow})$, for cases C3D and C2D. As Figure 2a shows, at cloud base, cases $F^{\downarrow}_{C3D}$ and $F^{\downarrow}_{C2D}$ are nearly the same; however, their values may differ by as much as a factor of two within the cloud layer. The same is true for the upward fluxes $F^{\uparrow}$ that differ in the cloud, but have close values at cloud top (Figure 2a).

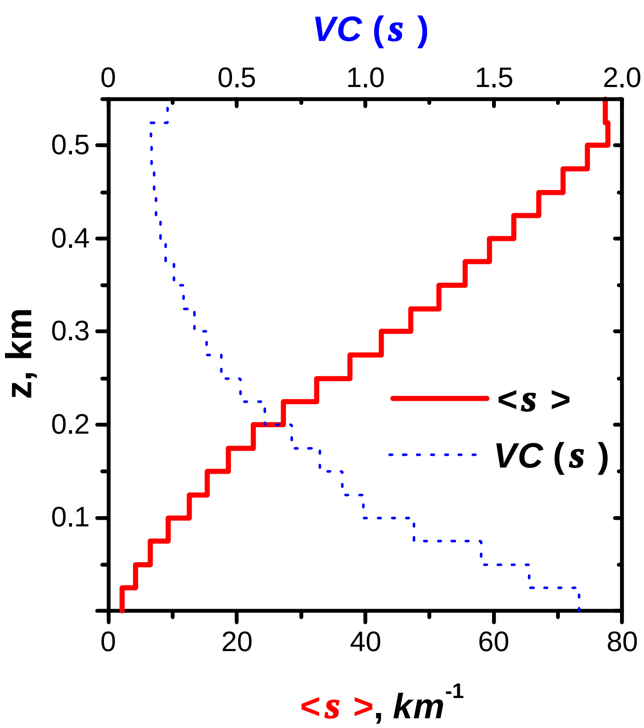

Figure 1. Vertical profiles of the mean and variation coefficient of extinction coefficient. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/kasyanov-98.pdf*.)

The variances of fluxes are more sensitive to the vertical stratification of the extinction coefficient and, thus, differ even more strongly than the mean values (Figure 2a,b). Like the means, they differ mostly within the cloud layer. For downward fluxes, the difference in variances in the cloud layer is more than 300%, while at the cloud base it is an order of magnitude less (Figure 2b). Maximum differences between the variances of upward fluxes are smaller, on the order of 50% (Figure 2b). We note that $Var(F^{\uparrow}_{C3D}) < Var(F^{\uparrow}_{C2D})$ at the cloud top, while $Var(F^{\downarrow}_{C3D}) > Var(F^{\downarrow}_{C2D})$ at the cloud base (Figure 2b). This is explained by the fact that photons scattered by the upper part of the cloud contribute most to its albedo; and the upper part of the cloud in the C3D is more homogeneous than in the C2D case. The opposite is true for transmittance.

We will now consider horizontal fluxes. The importance of the total radiative horizontal transport, between the cloud top and bottom boundaries, $E(\Delta H)$ has been studied extensively in the literature (e.g., Titov 1998). We will focus on the profiles of the variance of the horizontal transport (Figure 2d) and its effect on the variances of $F^{\downarrow}(z)$ and $F^{\uparrow}(z)$ (Figure 2c). As one can see, the neglect of horizontal transport leads to changes in the $Var(F^{\downarrow}_{C3D})$ and to an increase by a factor of 1.5-2 in the $Var(F^{\uparrow}_{C3D})$.

The inequality $Var(E_{C3D}) > Var(E_{C2D})$ holds for most vertical levels (Figure 2d). The variance of the horizontal transport has the maximum value in the upper portion of the cloud ($\Delta h \sim 0.15$ km) where there is also the maximum difference between $Var(E_{C3D})$ and $Var(E_{C2D})$ (Figure 2d). In the bottom portion of the cloud ($\Delta h \sim 0.4$ km), the differences in variance $Var(E)$ are smaller, exemplifying weaker dependence on vertical stratification of σ. The maxima of the Var(E) and $F^{\downarrow}$ are well correlated (Figure 2a, d). A similar correlation between the maxima of $F^{\downarrow}$ and mean absorptance, both for stratus and cumulus clouds was noted in Zuev and Titov (1995).

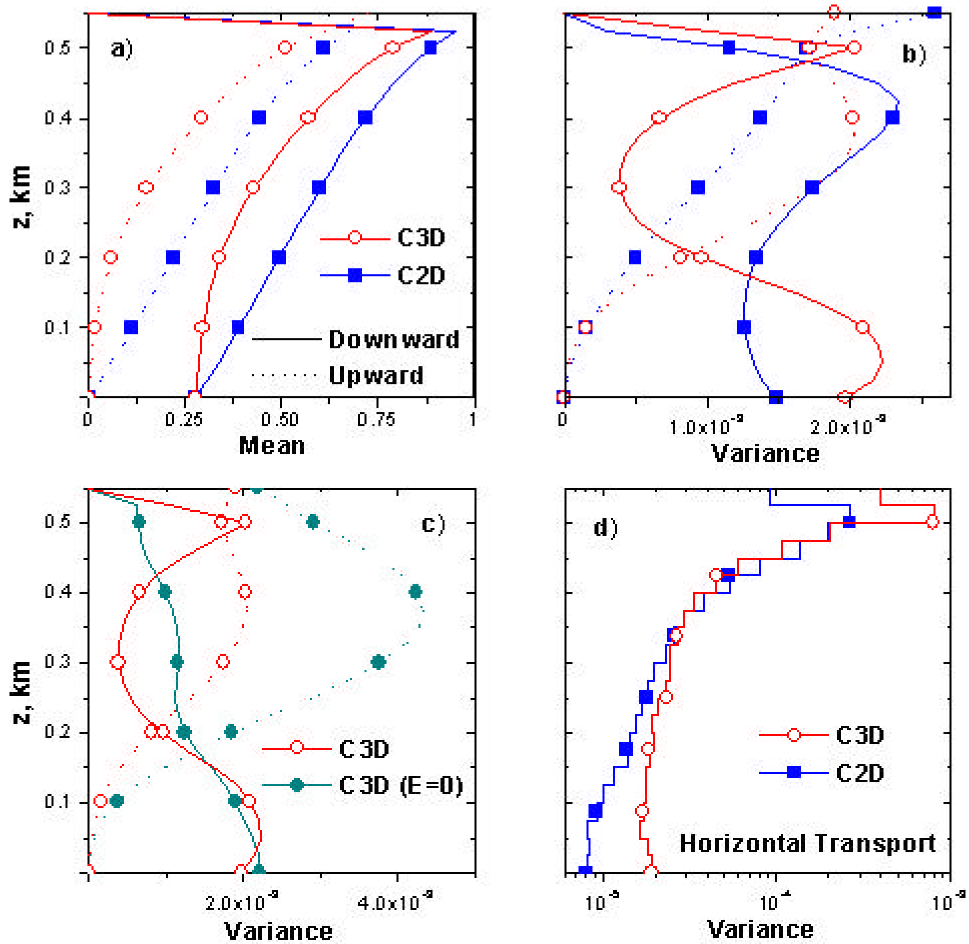

Figure 2. Vertical profiles of the mean and variance of downward and upward fluxes (a,b,c), and horizontal transport (d) for cases C3D and C2D. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/kasyanov-98.pdf*.)

Albedo and transmittance small-scale (on the order of 0.05 km) observations have been recently used for detailed studies of horizontal variability of cloud optical depth (Barker et al. 1996, Chambers et al. 1997, Davis et al. 1997) and cloud absorption (Marshak et al. 1997, Titov 1998). The neglect of horizontal transport degrades the accuracy of retrievals of these characteristics with larger errors at higher spatial resolutions. The spatial averaging of albedo and transmittance mitigates this effect. The averaging length depends not only on the mean and variance, but also on the spatial structure of albedo, transmittance, and horizontal transport. As our results show, the means and variances of albedo and transmittance depend weakly on the vertical profile of σ (Figure 2a,b). However, the latter has substantial influence on two-dimensional fields of albedo and transmittance (Figure 3). The spatial distribution of $E(\Delta H)$ is more sensitive to the vertical stratification of σ than the spatial distributions of albedo and transmittance (Figure 3).

Conclusions

A three-dimensional LES model of stratocumulus clouds with explicit liquid phase microphysics was used to study the influence of the vertical variability of the extinction coefficient on the mean, variance and spatial distribution of upward, downward, and horizontal radiative fluxes in the visible spectral range.

At the cloud boundaries, the means and variances of albedo and transmittance depend weakly on the vertical inhomogeneity of the extinction coefficient. Within the cloud layer, the vertical variability of the extinction coefficient

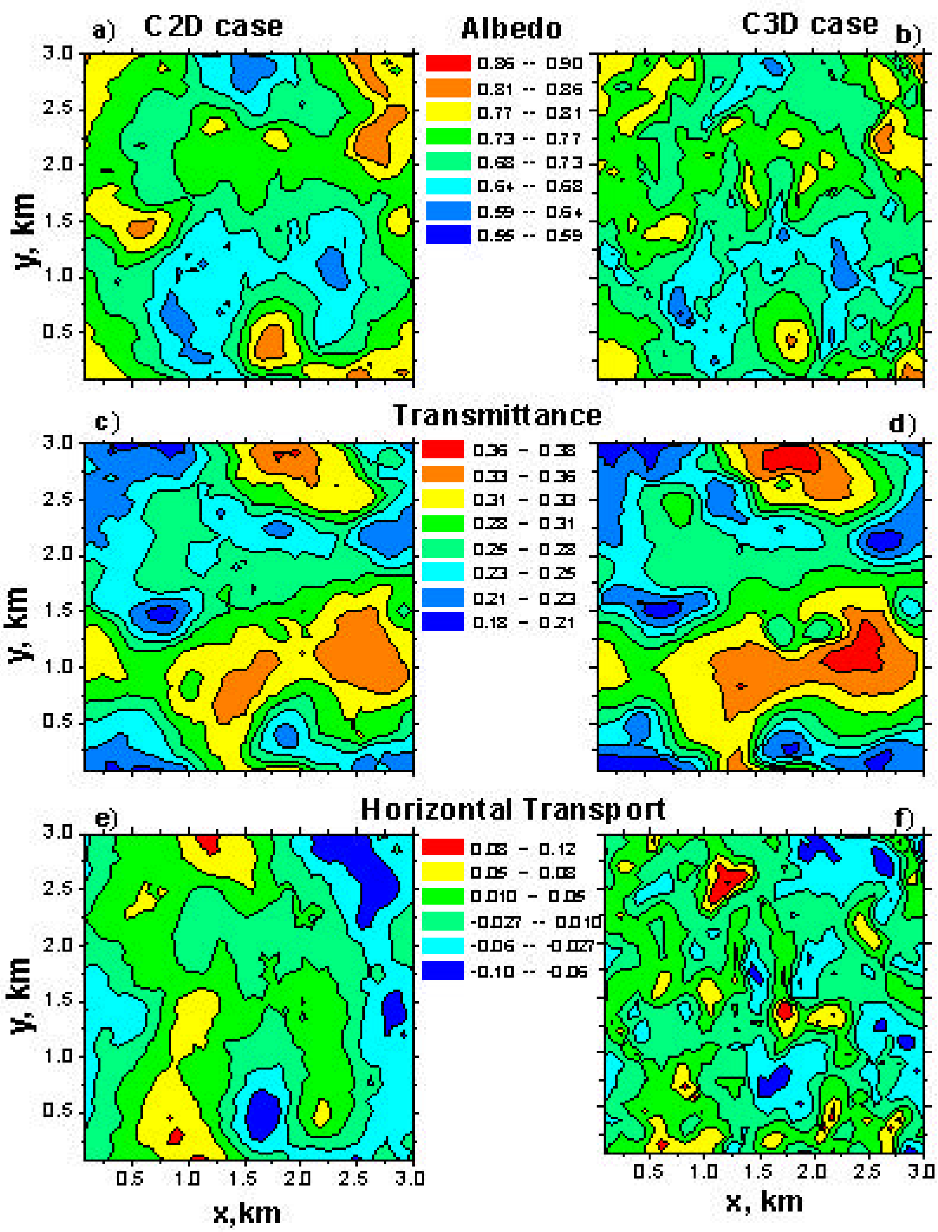

Figure 3. Two-dimensional fields of albedo, transmittance, and horizontal transport corresponding to C2D (left) and C3D (right) cases. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical conf_9803/kasyanov-98.pdf*.)

that results in about a factor of 2, decreases in the mean values and a factor of 2-3 changes in the variances of upward and downward fluxes.

The variance of horizontal transport peaks at cloud top, with the peak value of the same order of magnitude as the variance of upward and downward fluxes; deeper into cloud, it is about 1-2 orders of magnitude smaller. The maxima of the variance of horizontal transport and mean downward flux correlate well. The neglect of vertical variability of the extinction coefficient results in a factor of 4 decrease of the peak value of the horizontal transport variance.

The vertical stratification of the extinction coefficient has considerable effect on the spatial distribution of albedo and transmittance. The spatial distribution of horizontal transport in cloud layer, compared with that of albedo and transmittance, is even more sensitive to the vertical profile of the extinction coefficient. These facts may have an important bearing on retrieval of cloud parameters from satellite and ground observations.

We also conclude that the neglect of horizontal transport significantly affects the variance of upward and downward fluxes and, thus, the thermodynamics of the boundary layer. Therefore, the inclusion of horizontal radiative transport in the thermodynamical equations of the cloud scale models may be necessary to accurately account for cloud and boundary layer evolution.

We note that the extinction coefficient varies insignificantly in the 0.7 μm to 3.6 μm wave interval. Thus, the conclusions obtained in the paper for the visible range will also hold in the near-infrared range.

Acknowledgments

This research was supported by the ONR Grants N00014-96-1-0687 and N00014-96-1-1112 and by the Environmental Sciences Division of the U.S. Department of Energy (through Battelle Pacific Northwest National Laboratory Contract 144880-A-Q1 to CIMMS).

References

Barker, H. W., B. A. Wielicki, and L. Parker, 1996: A parameterization for computing grid-averaged solar fluxes for inhomogeneous marine boundary layer clouds. Part II: Validation using satellite data. *J. Atmos. Sci*, **53**, 2304-2316.

Chambers, L. H., B. A. Wielicki, and K. F. Evans, 1997: Independent pixel and two-dimensional estimates of Landsat-derived cloud field albedo. *J. Atmos. Sci*, **54**, 1525-1532.

Davis, A. B., A. Marshak, R. F. Cahalan, and W. J. Wiscombe, 1997: The Landsat scale break in stratocumulus as a three-dimensional radiative transfer effect: Implications for cloud remote sensing. *J. Atmos. Sci.*, **54**, 241-260.

Kogan, Y. L., 1991: The simulation of a convective cloud in a 3-D model with explicit microphysics. Part I: Model description and sensitivity experiments. *J. Atmos. Sci*., **48**, 1160-1189.

Kogan, Y. L., M. P. Khairoutdinov, D. K. Lilly, Z. N. Kogan, and Q. Liu, 1995: Modeling of stratocumulus cloud layers in a large eddy simulation model with explicit microphysics. *J. Atmos. Sci*, **52**, 2923-2940.

Marshak, A., A. B. Davis, W. J. Wiscombe, and R. F. Cahalan, 1997: Inhomogeneity effects on cloud shortwave absorption measurements: Two-aircraft simulations. *J. Geophys. Res.*, **102**, 16619-16637.

Titov, G. A., 1998: Radiative horizontal transport and absorption in stratocumulus clouds. *J. Atmos. Sci.*, in press.

Zuev, V. E., and G. A. Titov, 1995: Radiation effects in broken cloudiness. *Atmos. Ocean. Opt*., **8**, 105-114.