The Effect of Cloud Geometrical Thickness Variability on Optical Depth

Z. N. Kogan and Y. L. Kogan
Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, Oklahoma

Introduction

The formulation of the cloud-radiation feedback is compounded by extreme variability of clouds over a wide range of scales. In this study, we address the problem of geometry and spatial inhomogeneity in stratiform cloud layers and its influence on cloud optical depth. The investigation is based on the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) large eddy simulation model with explicit microphysics (Kogan et al. 1995). The two commonly used parameterizations of the cloud optical depth, which are based on simplified assumptions about cloud geometry and the spatial distributions of cloud parameters, are contrasted with the optical depth calculated using its exact definition as a second moment of the cloud drop distribution function. The goal of the study is to evaluate the bias introduced by different simplifications.

Approach

The exact definition of cloud optical depth *t* is

$$\tau(x,y,z) \geq \pi \int_{z}^{z_t} dz' \int_0^{\infty} Q_{ext} r^2 f(r,x,y,z')dr \qquad (1)$$

where Q_{ext} is cloud drop extinction function, r is the drop radius, and f(r, x,y,z) is the drop size distribution function; z is the level in the cloud. For $z = z_b$, $\tau(x,y,z_b)$ represents the optical depth for the whole cloud layer. The cloud base and top heights, z_b and z_t, also depend on x and y. The horizontally averaged τ (denoted by angular brackets) can be written as

$$\left\langle \tau(x,y,z) \right\rangle = \left\langle \frac{3}{2\rho_l} \pi \int_{z}^{z_t} \frac{Q(x,y,z')}{r_e(x,y,z')} dz' \right\rangle \qquad (2)$$

where Q is cloud liquid water, r_e is cloud drop effective radius, and ρ_l is the water density.

Due to the lack of microphysical data, Eq. (2) is often simplified by making a number of assumptions discussed in Kogan and Kogan (1997). Under these assumptions, Eq. (2) may be rewritten in several forms, e.g., $\tau_1(z)$ or $\tau_2(z)$.

$$\tau_1(z) = \frac{3}{2\rho_l} \int_{z}^{z_t} \frac{\left\langle Q(x,y,z') \right\rangle}{\left\langle r_e(x,y,z') \right\rangle} dz' \qquad (3)$$

The parameterization $\tau_1(z)$ represents an area averaged vertical profile of cloud optical depth and is often used in satellite retrievals (Nakajima and King 1990), as well as in modeling radiative effects in vertically inhomogeneous clouds (Li et al. 1994).

The parameterization $\tau_2(z)$ is obtained by applying the mean value theorem and rewriting Eq. (2) as

$$\tau_2(z) = \frac{3\left\langle LWP(x,y,z) \right\rangle}{2\rho_l r_e(z^*)} \qquad (4)$$

where <LWP> is the horizontally averaged liquid water path at level z, and $r_e(z^*)$ is the horizontally averaged value of $r_e(x,y,z^*)$. As the value of z* is not readily available, we make an additional assumption defining $r_e(z^*)$ as a horizontal mean value of the effective radius averaged also in the vertical from level z to the cloud top. Below we also consider some other possibilities of selecting $r_e(z^*)$ in order to estimate the sensitivity of Eq. (4) to this parameter.

Evaluation of Parameterizations

Parameterizations τ_1 and τ_2 are compared with the exact expression in Eq. (1) using the microphysical fields produced in two numerical simulations. The first one represents a midlevel thick stratiform cloud layer from z = 2.5 km to 6 km observed on 7 April 1997 during the intensive observation period (IOP) conducted over the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site. The cloud base was fairly flat. Because the temperature profile between 4 km and 6 km was only weakly stabilized, thermals with sufficient energy reached higher levels and produced a notably variable cloud top height.

The second case represents a marine low-level stratus layer observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) field program. The strong capping inversion resulted in a fairly uniform cloud top; however, the heterogeneous distribution of surface fluxes and drizzle in a turbulent boundary layer resulted in a highly variable cloud base. The distinction between the two cases is clearly demonstrated by the vertical profiles of cloud cover, liquid water content (LWC), effective radius, and the probability distribution of cloud depth (Figure 1). The histogram of the cloud depth distribution (not shown) in the ASTEX case is closer to Gamma-type distribution than in the ARM case where it is more uniform. In both cases, the cloud layer is not overcast through its whole depth.

Each simulation produced 1600 (40 x 40) vertical columns (pixels) covering an 8 km^3 and 2 km^3 domain in the ARM and ASTEX cases, respectively. For each column, the vertical profile of optical depth was calculated. These values are used in calculations of area averaged cloud optical depth. Plots below show the performance of parameterizations τ_1 and τ_2 as compared to the benchmark solution given by Eq. (1) for the column τ, and Eq. (2) for the averaged τ. Figure 2 compares area-averaged profiles of τ for the ARM case using the following different definitions of cloud geometrical depth: 1) H = H_Q, defined

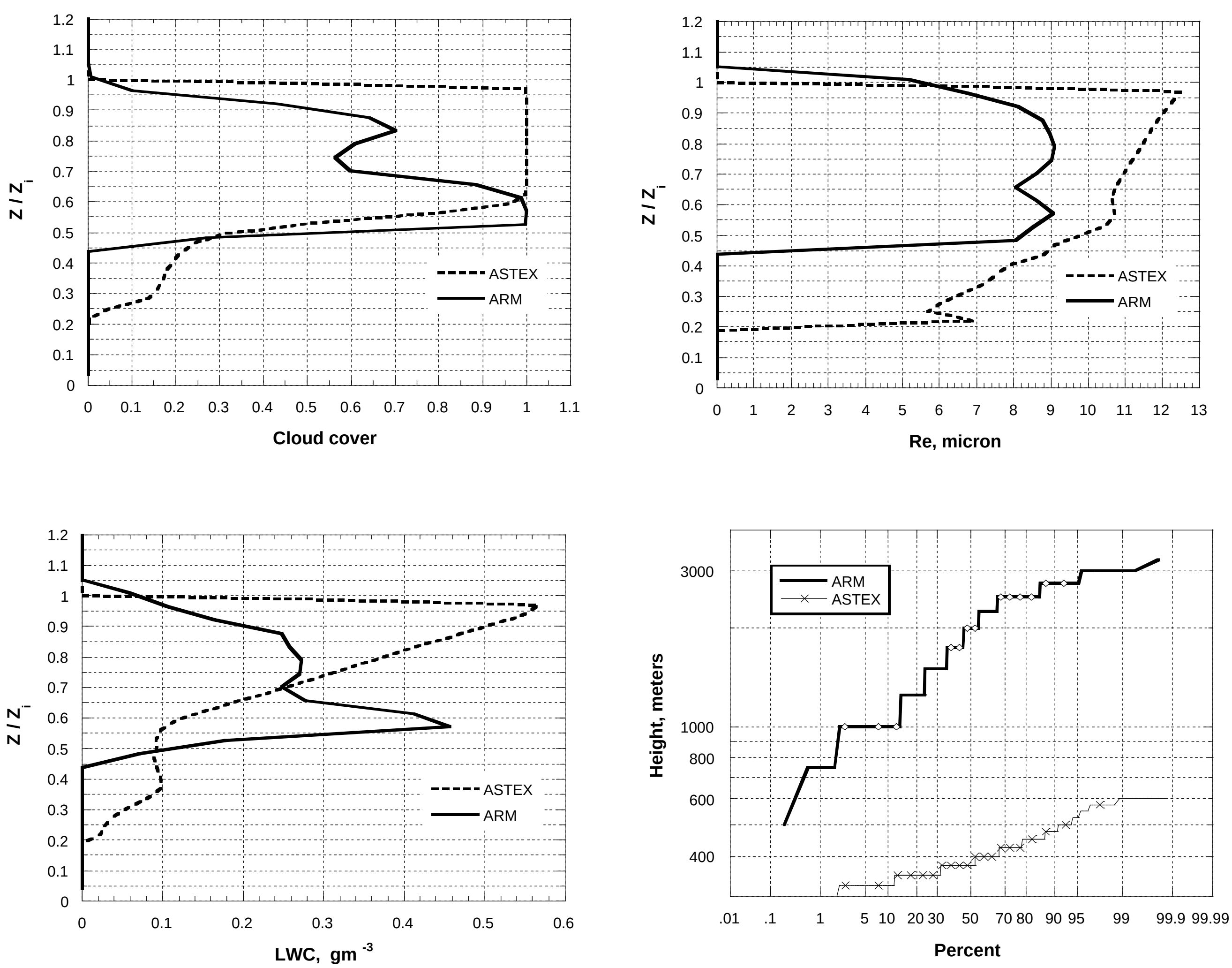

Figure 1. The horizontally averaged profiles of cloud cover, LWC, and effective radius, as well as probability distribution function of cloud geometrical depth for ASTEX and ARM cases.

by the minimum top and bottom threshold values of <Q(z)>; and 2) H= H_m, defined as a horizontal mean geometrical depth over all columns. The parameterization τ_1 using the definition of cloud geometrical depth H_Q overestimates the true value of optical depth by about 45%. The bias is caused mainly by the variability of cloud geometrical depth, as well as by the fact that cloud cover profile is less than 1 at some levels (Figure 1). The other source of bias, caused by approximation of the mean of the ratio <Q/r_e> by the ratio of the means <Q>/< r_e>, affects the optical depth only insignificantly (compare curves P1 and P1a in Figure 2). The error for the full optical cloud depth can be reduced if one uses the horizontal mean value of cloud geometrical depth H_m, which currently is not readily available from the data, except for numerical model data. However, the error in the optical depth, as well as in the extinction coefficient at any given cloud level (not shown here) is still significant (about 14%). The comparison results for the ASTEX case demonstrate the errors of similar magnitude.

The performance of the parameterization τ_2 using different values of the effective radius is shown in Figures 2 and 3. Figure 2 presents calculation results of the horizontally averaged profile of optical depth. The curve P2 uses the horizontally averaged value of r_e as in Eq. (4). To estimate the sensitivity to the value of r_e, we also used 1) a constant value of r_e, equal to its value at cloud top, 2) a prescribed value of 10 μ commonly used in large scale models, and 3) a value r_e^{exp} that can be estimated from experimental data on the cloud mean values of Q and N (Martin et al. 1994, JAS):

$$r_e^{exp} = \left(\frac{3Q}{4\pi\rho\kappa N} \right)^{1/3}$$

where $\kappa = 0.8$.

Eq. (4) gives the most accurate expression for the optical depth when one uses the average over the entire volume value of r_e.

Figure 3 shows the scattergram, which compares exact τ and τ_2 for each column. Crosses represent the case when all columns have the same height H_Q, circles represent the case when the exact value of H is calculated for each column but $r_e = 10$ microns, and diamonds represent the case when r_e is averaged over the column. Figure 3 shows that the τ_2 slab approximation introduces the largest errors, as was the case with the τ_1 parameterization.

Conclusions

We showed that the parameterization τ_2 is very sensitive to the value of the cloud drop effective radius, r_e, and works when r_e is *averaged both in horizontal and in vertical*. Using a-priori prescribed value of r_e may lead to errors as large as 30% to 60%. The error introduced by using the cloud top value of the effective radius is case dependent: the optical depth is significantly overestimated in the ARM case, but the error is less in the ASTEX case. The use of a

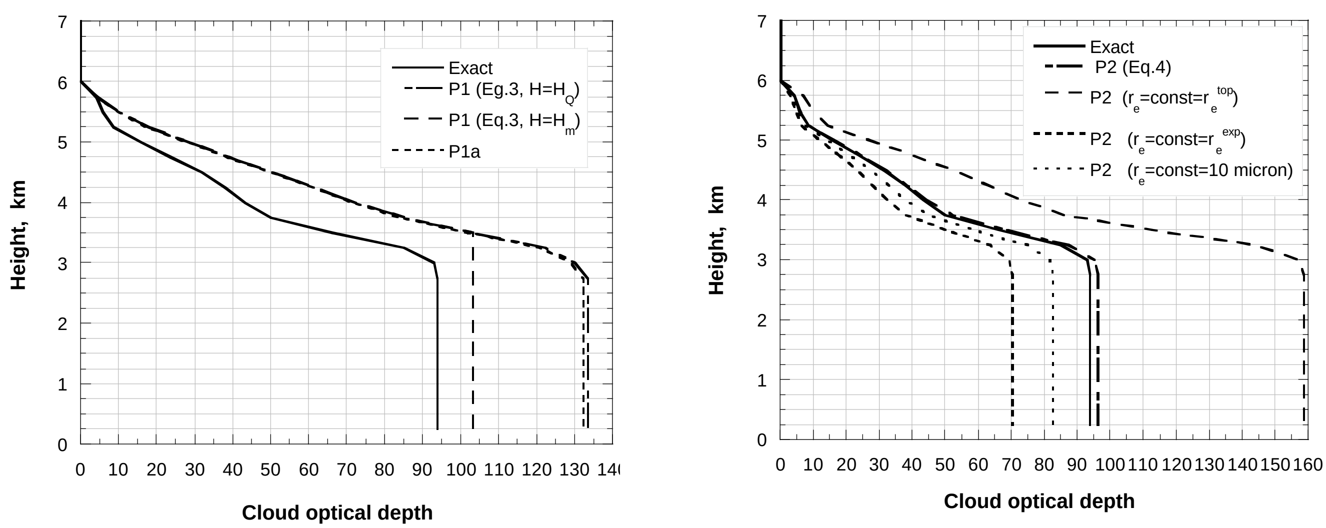

Figure 2. The horizontally averaged profiles of cloud optical depth for the ARM case calculated using the exact formula from Eq. (2) and different parameterizations (see text for details).

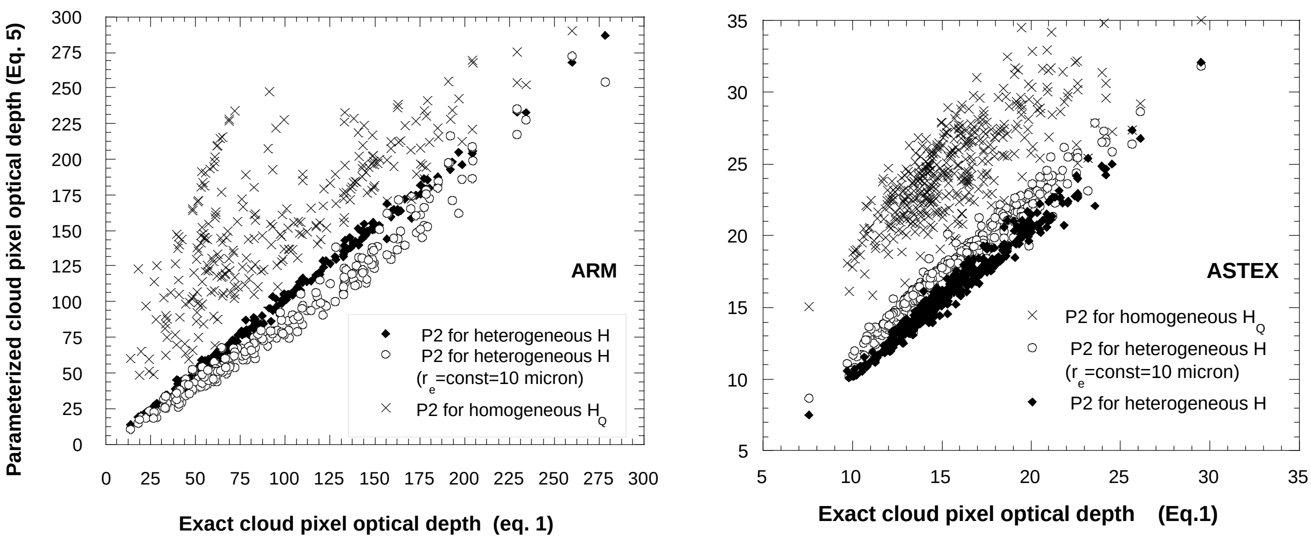

Figure 3. The scattergram of parameterized versus exact values of cloud optical depth calculated for each cloud column for ARM and ASTEX cases (see text for details).

prescribed value of 10μ, as well as the value r_e^{exp}, underestimates the optical depth in the ARM case from 10% to 30%.

The previous studies showed that the account for vertical stratification of LWC and cloud drop effective radius is important for calculation of the true value of cloud optical depth. Our results suggest that the account for the variation of cloud top and base boundary height is even more important than variations in cloud microstructure. Neglect of irregular cloud boundary height can lead to 20% to 45% errors in optical depth. The more cloud cover profile departs from 1 (i.e., overcast conditions), the larger the error that will be introduced by using the cloud slab assumption.

We also emphasize that the conventional use of a cloud cover as a single scalar parameter may not be sufficient for cloud optical depth calculations. When complex cloud geometry is considered, the vertical cloud cover profile should be used instead.

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