The Inhomogeneity of Stratocumulus Cloud Microstructure and Its Effect on Cloud Optical Depth

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Introduction

Due to computer limitations, most large-scale models rely on fixed prescribed *a priori* cloud microphysical parameters. Observations, however, show that such parameters are highly variable both in space and time.

In this study, we address the problem of spatial inhomogeneity in marine stratocumulus cloud layers. 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 cloud physics processes are fomulated using two distribution functions: one for cloud condensation nuclei and another for cloud drops. The short and long wave radiative processes are treated interactively using microphysical information available in the model. The two commonly used parameterizations of the cloud optical depth, which are based on simplified assumptions about the vertical profiles 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 is given as

$$\tau(x,y,z) = \pi \int_z^{z_{top}} dz' \int_0^\infty Q_{ext}\, r^2 f(r,x,y,z')\,dr \tag{1}$$

The correct horizontal average of τ (denoted by angular brackets) is

$$<\tau(x,y,z)> = <\pi \int_z^{z_{top}} dz' \int_0^\infty Q_{ext}\, r^2 f(r,x,y,z')\,dr>$$

$$= < \frac{3}{2\rho_l} \int_z^{z_{top}} \frac{Q(x,y,z')}{r_e(x,y,z')}\, dz'> \tag{2}$$

The formula (2) is often simplified in large-scale models where the information on drop size distributions is unavailable. Neither is the information on the horizontal variability of liquid water content and effective radius on the scale of 100 m or less.

A number of assumptions can be made in order to simplify (2):

1. The horizontal inhomogeneity of Q and r_e is neglected, but their variability in the vertical is taken into account.

   The horizontal average of a ratio can be approximated as a ratio of average values. Both of these assumptions introduce errors which will depend on the relative horizontal dispersions of $\sigma_Q/<Q>$ and $\sigma_{r_e}/<r_e>$.

Using these assumptions (2) may be rewritten as

$$\tau_1(z) = \frac{3}{2\rho l} \int_z^{z_{top}} \frac{<Q(x,y,z')>}{<r_e(x,y,z')>}\, dz' \tag{3}$$

The parameterization τ_1, which takes into account the vertical stratification of liquid water content and cloud drop effective radius is often used in satellite retrievals (Nakajima and King 1990), as well as in modeling of the radiative effects in vertically inhomogeneous clouds (Li et al. 1994).

2. The second parameterization may be obtained by applying the mean value theorem and rewriting of (2) as

$$< \frac{3}{2\rho_l r_e(x,y,z*)} \int_z^{z_{top}} <Q(x,y,z')>\, dz'> \equiv$$
$$\equiv < \frac{3LWP(x,y,z)}{2\rho_l r_e(x,y,z*)} > \tag{4}$$

Here LWP is the liquid water path at a given level z, and z* is an intermediate level between level z and the cloud top. Again, assuming that the horizontal average of a ratio can be approximated as a ratio of average values, we can rewrite (4) as

$$\tau_2\ (z) = \frac{3 < LWP(x,y,z) >}{2\rho_l R_e(z*)} \qquad (5)$$

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* cannot be determined from the mean value theorem, we define $R_e(z*)$ as a horizontal mean value of the effective radius averaged also in the vertical from level z to the top of the cloud.

Results

Parameterizations τ_1 and τ_2 are compared with the exact expression (1) using the microphysical fields produced in a simulation based on the observations obtained by Nicholls (1984). The simulation produced 1600 (40x40) vertical columns that can be considered independently in calculations of the cloud optical depth. We consider two stages of the cloud layer evolution. At the first stage (8100 s into the simulation), significant drizzle has developed and reached the surface. At the second stage (3 hours into the simulation) the drizzle ended, and the average LWP decreased from 158 to 120 g/m^2.

Figure 1 shows comparison results for the two stages in cloud evolution. It can be seen that the parameterization given by τ_2 is very close to the exact value of τ. Parameterization τ_1, which takes into account the vertical stratification of liquid water content and cloud drop effective radius, surprisingly enough, can significantly overestimate the true value of cloud optical depth. The good agreement given by expression (5) indicates that the determination of the value of the cloud drop effective radius *averaged both in horizontal and in vertical* is much more important than the account for vertical inhomogeneity as represented by approximation (3).

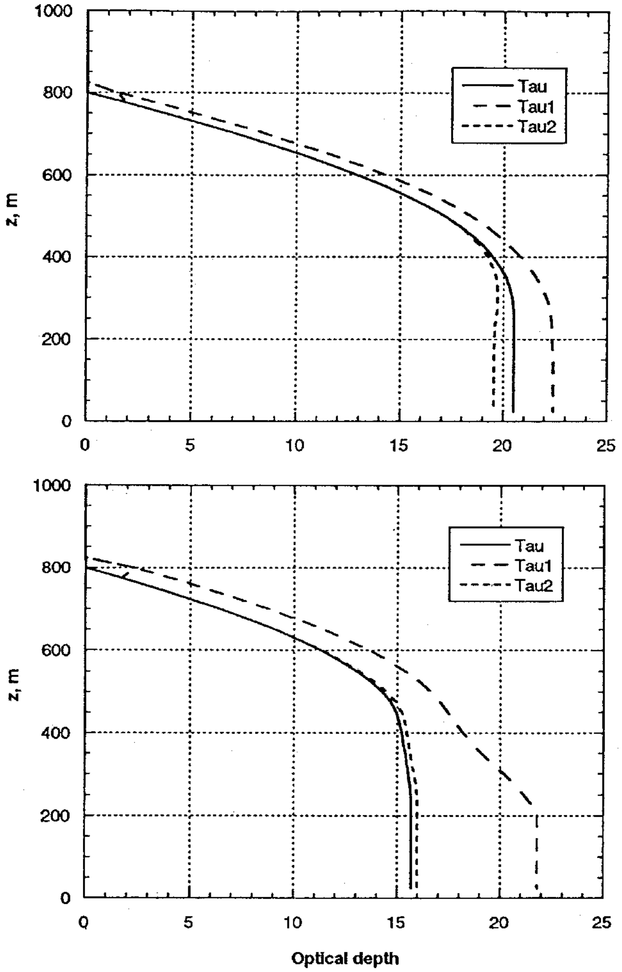

Figure 1. Vertical profiles of the cloud optical depth given by the exact expressions (curve marked "Tau") with parameterizations given by formula (3) ("Tau1") and (5) ("Tau2"). The top and bottom plots correspond to the simulation time of 8100 s and 10800 s, respectively.

Acknowledgments

This research was supported by the Environmental Sciences Division of U.S. Department of Energy (through Pacific Northwest National Laboratory PNR Contract 144880-A-Q1 to the Cooperative Institute for Mesoscale Meteorological Studies) as part of the Atmospheric Radiation Measurement Program. Support for this research was also provided by the ONR Grant N00014-96-1-0687 and by the National Oceanic and Atmospheric Administration's Climate and Global Program under the Grant NA37RJ0203.

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