Development of an Elevated Mixed Layer Model for Parameterizing Altocumulus Cloud Layers

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Introduction

Altocumulus (Ac) clouds play an important role in the earth's energy budget through their effects on solar and infrared radiation, yet they are typically too thin to be vertically resolved in global climate models. Ac layers have been either neglected or implicitly represented through a "fractional cloudiness" scheme in climate models (Randall et al. 1989). Since such schemes are empirically rather than physically based, they are not suitable for climate change prediction.

Radiosonde measurements and our cloud-resolving model (CRM) simulations indicate that Ac layers are approximately well-mixed (Liu and Krueger 1996). This suggested that Ac layers may be parameterized using an elevated mixed layer model (MLM). In this paper, we report on the development and testing of an elevated MLM for Ac. This is a step toward incorporating a physically based parameterization for thin Ac layers into a general circulation model. First, we introduce the CRM and Ac MLM. Then, we briefly discuss a cloud water snapshot of the Ac layer. Finally, we compare some cloud characteristics from the CRM and Ac MLM simulations in order to test the MLM.

Description of Models

The CRM is based on the 2D (x-z) anelastic set of equations. It includes the hydrostatic, continuity, vorticity, thermodynamic, and total water equations. The CRM also includes a third-moment turbulence closure, a turbulence-scale condensation scheme, a bulk microphysics parameterization, and an advanced radiative transfer code. Neither ice-phase nor precipitation is considered in this study. The CRM is more fully described in Krueger (1988), Xu and Krueger (1991), and Krueger et al. (1995a,b). The radiative transfer parameterization used in the CRM is described in Fu (1991), Fu and Liou (1992), and Krueger et al. (1995a,b).

The mixed layer prognostic equations for elevated Ac mixed-layer moist static energy h_M, total water mixing ratio q_{wM}, top height z_T, and base height z_B are described in Liu and Krueger (1996). The turbulent fluxes of moisture static energy h and total water mixing ratio q_w at the Ac layer boundaries are also described in the above reference. To close the MLM, the entrainment velocities must be parameterized based on assumptions about the turbulent structure of the mixed layer. We use a closure which is based on the entrainment parameterization of Turton and Nicholls (TN 1987). The entrainment velocity at the mixed layer top is

$$w_{eT} = \frac{A}{(z_T - z_b)\,\Delta s_{vT}} \int_{zB}^{zT} \overline{w' s'_v}\, dz$$

where s_v is the virtual dry static energy and Δs_{vT} is the jump in s_v across the upper inversion layer. We set the constant A=2.5. We do not directly determine w_{eB}. Instead, we use TN's decoupling condition:

$$BIR = \frac{\int_{z_B}^{z_C} \overline{(w' s'_v)}\, dz}{\int_{z_C}^{z_T} \overline{(w' s'_v)}\, dz} < BIR_{max},$$

where z_c is the height of the cloud base, and BIR_{max} is a negative constant representing the maximum allowable turbulent kinetic energy loss due to buoyant consumption. As the mixed-layer top rises due to entrainment, z_B must typically also rise to prevent BIR from falling below BIR_{max}.

Simulations and Results

The profiles of potential temperature θ and water vapor mixing ratio q_v we used to simulate a thick cloud and a thin cloud are similar to those used by Starr and Cox (SC 1985b). These are shown in Figures 1a and 1b, respectively.

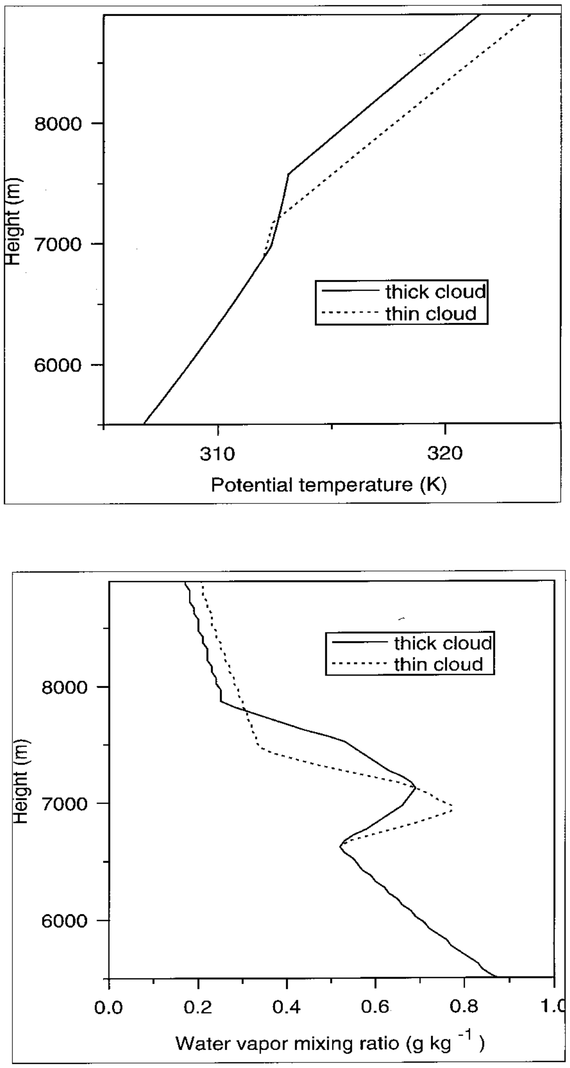

Figure 1. Initial profiles of (a) potential temperature and (b) water vapor mixing ratio for a thin and a thick cloud of CRM simulations.

The model domain is 6.4 km long and 8.9 km high. The horizontal grid interval is 100 m, while the vertical grid interval is 1 km from surface to 5 km, 500 m from 5 to 5.5 km, and 50 m from 5.5 to 8.9 km. The time step is 5 seconds. For the thick cloud simulations, θ and q_v from 5.5 km to 8.9 km are initialized the same as in SC. As the thick cloud depth is thicker than the normal Ac cloud depth, we also simulated a thin cloud for which the initial supersaturation region is half of the thick cloud.

To initiate motions, random perturbations in potential temperature are used. The maximum initial magnitude of the perturbations is 0.1 K. The resulting surface turbulent flux is near zero. The solar radiation for these cases is zero, corresponding to nocturnal conditions. The total simulation time is 6 hours.

In Figure 2, the simulated field of liquid water mixing ratio q_c for the thick cloud simulation at t = 1 hour is displayed.

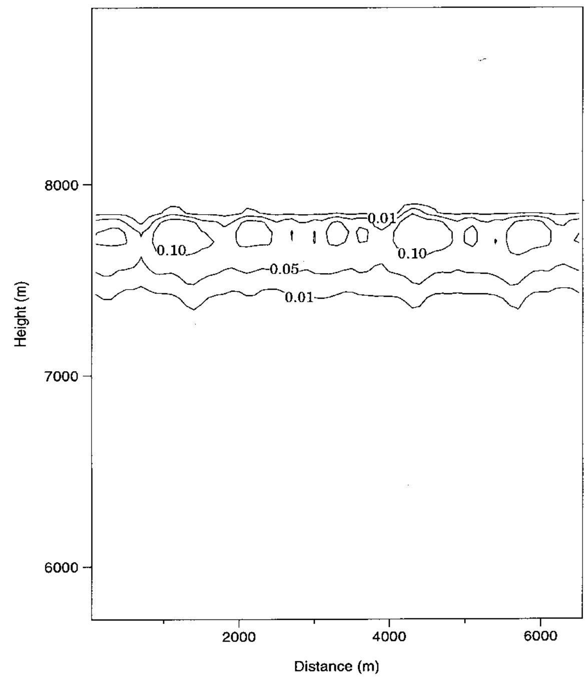

Figure 2. Contour plot of the cloud water mixing ratio (g/kg) at time t = 1 hour for the thick cloud of CRM simulations.

This q_c snapshot is typical of both simulations. There are several cells, or regions of larger q_c, which are due to updrafts.

As there is not a mixed layer in the initial profiles used for the CRM simulations, we use the profiles from the last 5 minutes of the first hour of the CRM simulations as the initial conditions for the MLM simulations. For the moist static energy and total water mixing ratio at the inversion top (assumed to be 50 m above the mixed layer top), we use the following linear relations derived from the CRM simulations:

h_T+(J/kg) = 3.84131z + 284574
q_{wT}+(g/kg) = -1.12565×10^{-4}z + 1.11125 for the thick cloud
h_T+(J/kg) = 3.53798z + 287848
q_{wT}+(g/kg) = -2.29849×10^{-4}z + 0.993865 for the thin cloud,

where z is the height in meters.

The radiation code used in the MLM is the same as the one used in the CRM. In order to calculate the radiative fluxes within the cloud layer, we divide it into twenty equal layers. We fixed the total number of levels above and below the mixed layer for convenience.

The value of BIR_{max} used in the MLM simulations is its average value in the CRM simulations between 1 and 6 hours. It is 0.0266 for the thin-cloud simulation and 0.0199 for the thick-cloud simulation. These values are about a tenth the size of the values used by TN and Bretherton and Wyant (1997) for the STBL.

The simulated Ac layers rise due to entrainment at cloud top and detrainment at the mixed layer base. Figures 3a and 3b show that in the simulations, the cloud top entrainment velocity decreases slowly and its values are between 1-3 cm^{-1}.

The evolution of the LWP for the CRM and MLM simulations of thin and thick Ac cloud layers is compared in Figures 4a and 4b, respectively. In the MLM simulation of the thin cloud, the LWP decreases about 30% during the first 2 hours, then becomes steady. However, in the corresponding CRM simulation, the LWP remains near its initial value. In the MLM simulation of the thick cloud, the LWP remains close to its initial value, while it decreases by nearly 40% during the CRM simulation. It is interesting that the LWP reached a quasi-steady value in both MLM simulations. The agreement between the LWPs from the MLM and the CRM simulations is only fair. However, it is difficult to predict this quantity accurately. For example, the range of LWP at the end of 2-hour-long simulations of a stratocumulus-topped boundary layer (STBL) by six 1-D models and ten large-eddy simulation (LES) codes was about equal to the average LWP (Bechtold et al. 1996).

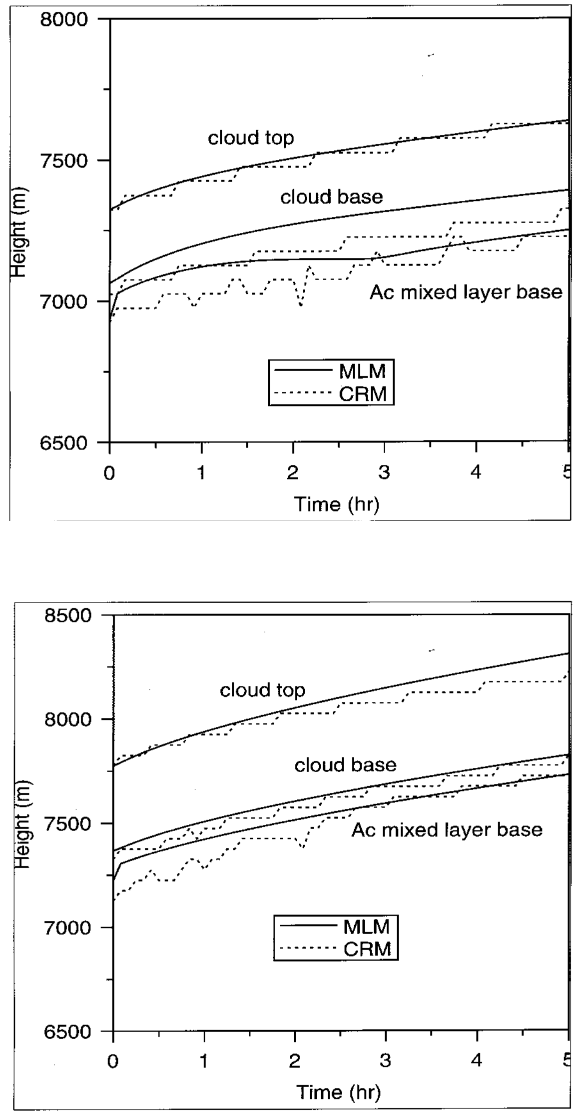

Figure 3. Evolution of cloud base and top heights, and Ac mixed layer base for (a) the thin cloud and (b) the thick clouds of the CRM and MLM simulations, respectively.

Summary

We have developed and tested an elevated MLM for Ac. The Ac MLM uses a method for determining the entrainment rate at the mixed layer top that is used in many MLMs of the STBL. At the mixed layer base, the Ac mixed-layer model detrains at a rate that keeps BIR, the ratio of buoyant consumption of turbulent kinetic energy in the subcloud layer to buoyant production in the cloud layer, equal to BIR_{max}. This approach is based on that used by Turton and Nicholls (1987) in their multiple mixed layer model. The numerical value of BIR_{max} determined from CRM simulations of Ac layers is about 0.02, which is about a tenth the size of the values used by TN and Bretherton and Wyant (1997) for decoupled STBLs.

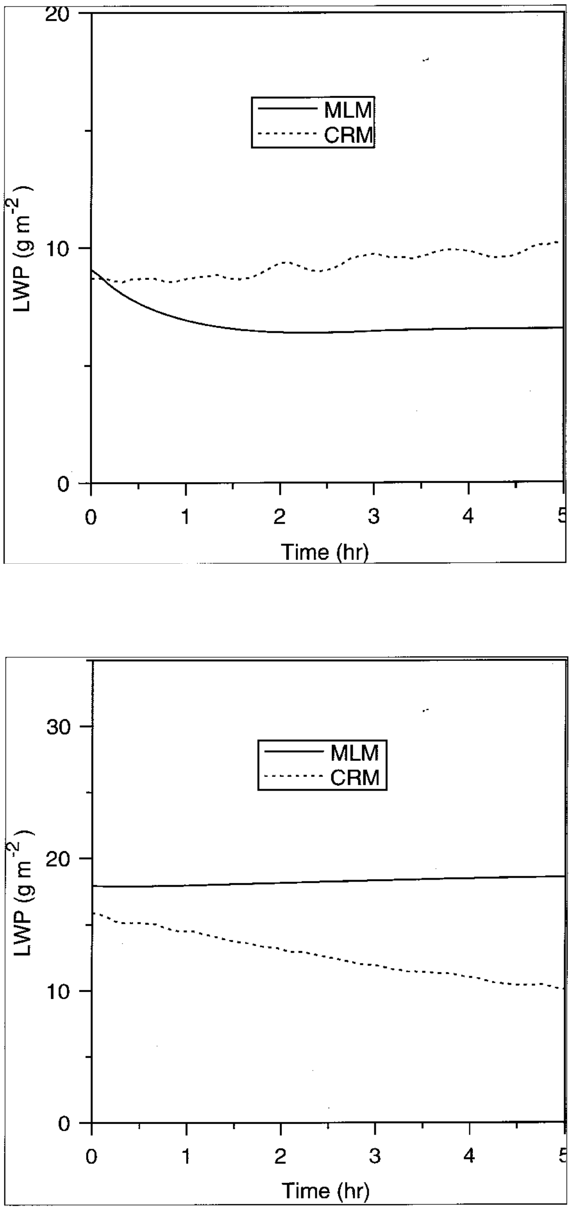

Figure 4. Evolution of the vertically integrated liquid mixing ratio (LWP) for (a) the thin cloud and (b) the thick clouds of the CRM and MLM simulations, respectively.

To test the Ac MLM, we compared results from it with those from a CRM for a thin Ac layer and a thick Ac layer. The MLM results were good compared with the CRM results for the cloud top, cloud base, and mixed layer base heights, and fair for the LWP.

Acknowledgments

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