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SOME ASPECTS OF TURBULENCE-MICROPHYSICS INTERACTION IN NUMERICALLY SIMULATED STRATOCUMUOLUS CLOUDS

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1. INTRODUCTION

Condensation and turbulent liquid water transport in stratocumulus clouds involve complicated interactions between turbulence dynamics and cloud microphysical processes, and play essential roles in defining the cloud structure. Consequently, any coupled turbulence-microphysics parameterization critically depends on our understanding of the interaction process. An important question is how the turbulence interact with the microphysics to contribute to the ensemble mean CE rate and the fluxes?

This work is focused on this issue with a LES-Bin microphysical model. The approach is to analyze budgets of liquid water content ($\bar{q}_l$) turbulent liquid water flux ($\overline{w' q_l'}$) based on a LES Bin-Microphysical model results. We then perform several simulations to understand results from the budget analysis.

2. LES BIN-MICROPHYSICAL MODEL

The LES model used in this study is that of Stevens (1999) and the bin-microphysical model is that developed by Feingold (1994). Readers are referred to these papers for a comprehensive review and evaluation of these models.

3. BUDGET EQUATIONS

The starting point for the budgets is the equation for the change of droplet spectrum due to condensation and evaporation (CE):

$$\left(\frac{\partial n}{\partial t}\right)_{ce} = -\frac{\partial}{\partial r}\left(\frac{n\,G(T,p)S}{r}\right), \tag{1}$$

where *n(r)* is the droplet size distribution function, *G(T,p)* a weak function of temperature and pressure, *S* supersaturation [$S=(q_t-q_l-q_s)/q_s$], and *r* radius of a single cloud droplet. A third-moment integration gives the CE rate

$$\left(\frac{\partial q_l}{\partial t}\right)_{ce} = 4\pi G\rho_l RS\,, \tag{2}$$

where *R* is the integrated radius. Applying Reynolds averaging operation gives the following ensemble mean CE rate:

$$\left(\frac{\partial \bar{q}_l}{\partial t}\right)_{ce} = 4\pi G(\bar{T},\bar{p})\rho_l(\bar{R}\bar{S}+\overline{R'S'}), \tag{3}$$

$$\frac{\partial \bar{q}_l}{\partial t} = \underset{T}{-\frac{\partial\,\overline{w'q_l'}}{\partial z}} + \underset{CE}{4\pi C\rho_l\left[\underset{1}{\bar{R}\,\bar{S}} + \frac{\bar{R}}{3}\left(\underset{2}{\frac{\overline{q'S'}}{\bar{q}_l}} + \underset{3}{\frac{2\,\overline{N'S'}}{\bar{N}}}\right)\right]} \tag{4}$$

where a log-normal distribution is used to approximate $\overline{S'R'}$ and the numbers represent individual terms

By subtracting (3) from (2), we may also have fluctuating condensation/evaporation rate which is needed to derive following $\overline{w'q_l'}$ equation

$$\begin{aligned}\frac{\partial\,\overline{w'q_l'}}{\partial t} &= \underset{T}{-\frac{\partial\,\overline{w'w'q_l'}}{\partial z}} \underset{G}{- \overline{w'^2}\frac{\partial \bar{q}_l}{\partial z}} \underset{B}{+ \frac{g}{\theta_0}\overline{\theta_v' q_l'}} \underset{P}{- \frac{1}{\rho_0}\overline{q_l'\frac{\partial p'}{\partial z}}}\;. \\ &\quad \underset{M}{+4\pi G\rho_l\left[\underset{1}{\bar{R}\,\overline{w'S'}} + \underset{2}{\bar{S}\,\overline{w'R'}} + \underset{3}{\overline{w'S'R'}}\right]} + \overline{w'A_c'}\end{aligned} \tag{5}$$

4. RESULTS

The budget of $\bar{q}_l$ is presented in Fig 1a, where

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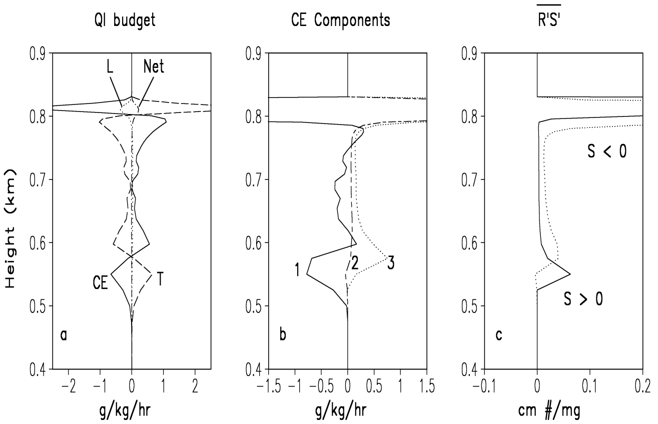

Figure 1 Liquid water budget

there is a clear balance between condensation and the divergence of $\overline{w' q_l'}$. Fig 1b shows that the mean saturation ($\overline{S}$) term mainly make negative contribution, while other two turbulence correlation contribute positively. Particularly, $\overline{S' N'}$ term is significant clearly due to the droplet activation at the cloud base. Fig. 1c shows the conditionally sampled $\overline{S' R'}$, which is positive for both *S* < 0 and S > 0. This means that the turbulence correlation enhances the condensation in updrafts while reduces evaporation in downdrafts. This budget result clearly indicates that the turbulence contribution to the ensemble CE must be included in microphysical parameterization.

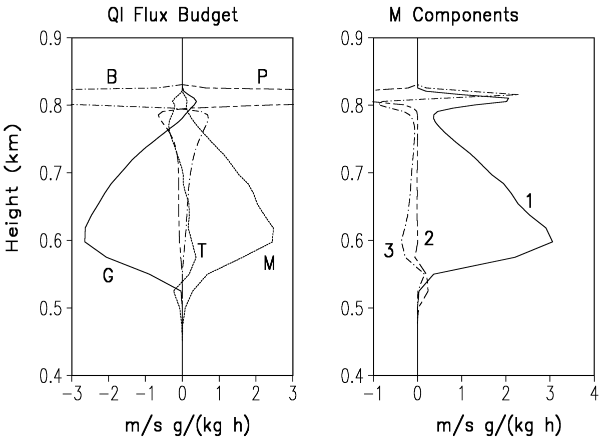

Figure 2 Liquid water flux budget

As shown in Fig. 2, the gradient (G) and microphysical (M) terms dominate in most of the cloud layer while the pressure and buoyancy terms make significant contributions near the cloud top. One may decompose the microphysics into three terms as shown in (5) and Fig 2b. The supersaturation flux is the dominant term among the three, leading to a relatively simple balance between the gradient and $\overline{w' S'}$. Actually, one could start Lagrangian supersaturation equation to give following:

$$\overline{w' S'} \cong -\frac{\overline{w'^2}}{4\pi G\, \overline{R}} \frac{d\,\overline{q}_{sa}}{d\,z}, \tag{6}$$

which shows that $\overline{w' S'}$ is what is needed to balance the gradient term. Therefore, the liquid water flux results from the close balance between the down-gradient transport and the supersaturation flux, clearly because *S* is the most critical driving force for the condensation and *w* and *S* are highly correlated.

Using the definition of supersaturation, one can give

$$\overline{w' S'} \cong \overline{w' q_t'} - \frac{c_p\, \gamma}{L} \overline{w' \theta_l'} - (1+\gamma)\, \overline{w' q_l'} \tag{7}$$

which can be substituted into (5). After some assumptions are made to approximate the pressure term (Moeng, 1996) and the time derivative is set to zero, we have

$$\overline{w' q_l'} =$$

$$\frac{\tau_R \left(-\overline{w'^2} \frac{\partial\, \overline{q}_l}{\partial\, z} + 0.5 \frac{g}{\theta_0} \overline{\theta_v' \, q_l'} \right) + \frac{\tau_R}{\tau_{CE}\,(1+\gamma)} \left(\overline{w' q_t'} - \frac{c_p\, \gamma}{L} \overline{w' \theta_l'} \right)}{1 + \frac{\tau_R}{\tau_{CE}} \left(1 - \frac{\overline{S}}{\overline{q}_l\,(1+\gamma)} \right)} \tag{8}$$

where τ_R is the return-to-isotropy time scale whose magnitude is of the same order as the large-eddy turnover time (Moeng, 1986), and τ_{CE} the *CE* time scale defined by

$$\tau_{CE} = [4\pi\, \rho_l\, (1+\gamma) \overline{G}\, \overline{R}]^{-1} \tag{9}$$

Equation (8) states that the liquid water flux depends on two time scales: large-eddy turbulence (5-10 min.) and the condensation time (3-10 sec.) scales. Unlike any other previous parameterization, (8) relates the liquid water to cloud droplet spectrum through the integral radius R.

The differences among (8), the LES and other parameterizations can be clearly seen in Fig. 3 where the mass-flux scheme and the statistical scheme by Sommeria and Deardorff (1977) are also shown. The newly developed scheme is very consistent with the LES results.

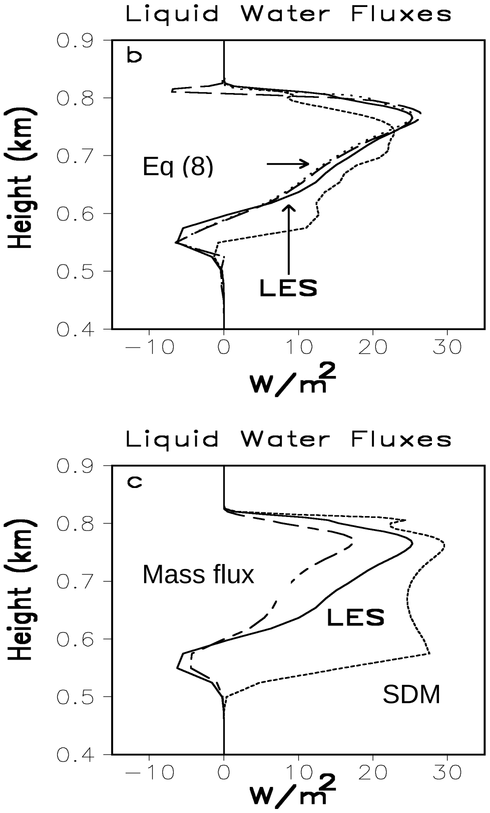

Figure 3: Comparison among different schemes

It is interesting to note that the statistical scheme results in significantly larger $\overline{w'q_l'}$ than the LES even when the cloud fraction is 1. This difference can be explained in terms of (7). In common subgrid scale cloud parameterization, it is always assumed that the liquid water is condensed at its equilibrium level, termed saturation adjustment which assumes infinitesimally small CE time scale. For this cloud scheme, S=0 for any cloudy points, which means $\overline{w'S'}$=0 in (7). For a bin-microphysical model, the CE time scale is defined by (9) and is finite, which means S may be greater or less than zero. Furthermore, *w* is highly and positively correlated with *S*. Therefore, $\overline{w'q_l'}$ is reduced as a result of positive $\overline{w'S'}$ as shown in (7). Furthermore, $\overline{w'S'}$ is related to cloud spectrum through (6), which means large R (large N) tend to lead to small $\overline{w'S'}$. Consequently, $\overline{w'q_l'}$ is dependent on the droplet spectrum as demonstrated in (8). To test these ideas, we perform another two simulations. One is with CCN=1000/mg (N1000), another is with saturation adjustment scheme (SA) . The $\overline{w'q_l'}$, $\overline{w'S'}$ and liquid water content are presented in Fig. 4. It is seen that the flux result from N1000 is even closer to SA than the control Because there is more condensation (evaporation) in updrafts (downdrafts), turbulence is stronger in SA and N1000 compared with the control run. Consequently, more entrainment and less liquid water content result in SA and N1000. Therefore, cloud dynamics may be changed because of different CCN concentration even if there is no drizzle.

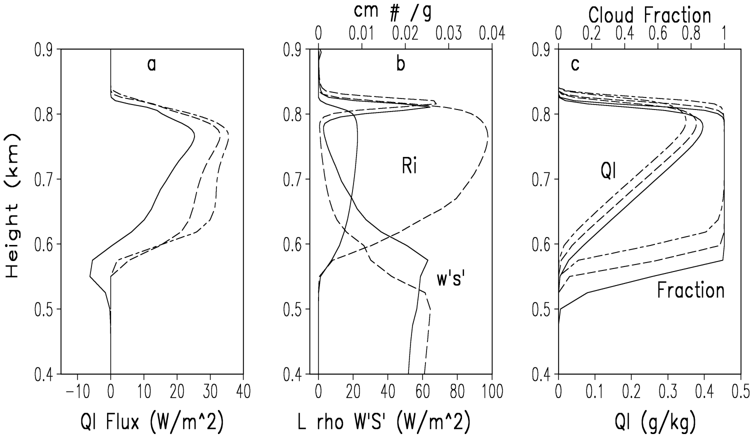

Figure 4: Impacts of N

5. IMPACTS OF DRIZZLE

The parameterization is derived based on the simulation without droplet coalescence, collection and sedimentation. There are two ways by which drizzle may affect the parameterization: significant contribution from the drizzle-turbulence correlation and significant change in the turbulence structure by drizzle. We have found that the contribution from drizzle-turbulence correlation is negligible. Therefore so long as the dynamics is basically driven by radiatively cooling at the cloud top (as compared to shallow cumulus dynamics), (8) should apply.

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