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COUPLING MICROPHYSICS PARAMETERIZATIONS TO CLOUD PARAMETERIZATIONS

Vincent E. Larson* Brian M. Griffin
Atmospheric Science Group, Dept. of Mathematical Sciences, University of Wisconsin — Milwaukee.

1. INTRODUCTION

Simulation of cloud dynamics and microphysics is complex. Consider the relatively simple problem of drizzle evolution in marine stratocumulus clouds. Drizzle production is greatest in parts of cloud where cloud water mixing ratio, r_c, is highest (all else being equal). Relatedly, the mean r_c may not be as relevant to mean drizzle production as the value of r_c in the moistest parts of cloud. This is an impediment for numerical models, which often use grid box means. More generally, two common complicating features of microphysical processes are that (1) they possess fine-scale variability; and (2) they are nonlinear.

One method of modeling such cloud and microphysical processes is large-eddy simulation (LES). These are three-dimensional simulations that resolve the large eddies inside and outside cloud, thereby calculating r_c in both moister and drier parts of cloud. However, LES models are too computationally expensive to be used to forecast weather or climate. Instead, weather and climate models use horizontal grid spacings of several kilometers or more. In these models, subgrid cloud and microphysical processes must be estimated, that is, parameterized (Arakawa 2004).

This parameterization problem is formidable. We desire a layer-cloud parameterization that is general in at least three respects. First, although the focus of this paper is stratocumulus, we desire a cloud parameterization that works equally well for other boundary layer cloud types, such as cumulus or cumulus-rising-into-stratocumulus. Second, we desire a cloud parameterization that allows us to model a wide variety of microphysical processes, including drop formation, growth, and fallspeed, but also other processes such as those involving ice. Third, we desire a cloud parameterization in which microphysics can interact on the subgrid scale with other processes such as turbulence and radiative transfer. For all these cloud types and physical processes, we need a consistent method to handle subgrid variability.

One method for handling subgrid variability is the assumed probability density function (PDF) method. This method predicts the joint PDF of relevant fields within each grid box and timestep. The single-column model (SCM) of Golaz et al. (2002) and Larson and Golaz (2005) models a joint PDF that includes vertical velocity (w), liquid water potential temperature (θ_l), and total water mixing ratio (r_t). Using this joint PDF, the SCM diagnoses not only the grid box average of r_c but also the full distribution (i.e. histogram) of r_c within the grid box. A chief advantage of predicting this detailed information is the ability to force microphysical processes at the subgrid scale. For instance, given the PDF of r_c, the drizzle drops "know" the amount of liquid in the moistest parts of cloud. Therefore, the drizzle drops "know" how fast to grow in these moist regions. Although the assumed PDF method was introduced into meteorology decades ago (Sommeria and Deardorff 1977; Mellor 1977; Manton and Cotton 1977), it has not been fully exploited for the purpose of driving microphysics with the full subgrid distribution of r_c.

In this paper, we extend our SCM (Golaz et al. 2002; Larson et al. 2005) to include drizzle produced by marine stratocumulus. This requires two steps. First, we must extend the joint PDF to include cloud droplet number concentration, N_c, drizzle mixing ratio, r_r, and drizzle number concentration, N_r. For these variables, we use a lognormal distribution, while retaining a Gaussian-mixture distribution for w, r_t, and θ_l. In combination, this forms a joint six-dimensional PDF for (w, r_t, θ_l, N_c, r_r, N_r). The second step is to integrate microphysical processes over the PDF. For instance, consider the process of "collection," in which drizzle drops grow via collision and coalescence with smaller cloud droplets. Collection is taken to be a function of cloud water mixing ratio, r_c, and drizzle mixing ratio, r_r. We may compute the grid box average collection rate, $\overline{A(r_c, r_r)}$, using the following integral:

$$\overline{A(r_c, r_r)} = \int_0^\infty \int_0^\infty P(r_c, r_r) A(r_c, r_r)\, dr_c\, dr_r. \quad (1)$$

Here P is the joint PDF of r_c and r_r, and $A(r_c, r_r)$ is the *local* collection rate, that is, the collection in a small cloud parcel. To perform this integral, several methods have been proposed. One method is Monte Carlo integration, in which the integrand is sampled statistically and then summed (Pincus et al. 2003; Räisänen et al. 2004; Räisänen and Barker 2004; Larson et al. 2005). In contrast, here we perform the integral analytically, which avoids the computation cost and statistical noise inherent in Monte Carlo integration.

Analytic integration is made possible by the fact that we assume a simple PDF shape (Gaussian-mixture/lognormal) and that we choose a simple microphysical scheme (Khairoutdinov and Kogan 2000). The Khairoutdinov-Kogan (KK) microphysics scheme is

**Corresponding author address:* Vincent E. Larson, Department of Mathematical Sciences, University of Wisconsin – Milwaukee, P. O. Box 413, Milwaukee, WI 53201-0413, vlarson at uwm dot edu, http://www.uwm.edu/∼vlarson .

a two-moment (r_r and N_r) scheme intended for modeling drizzle in stratocumulus. It parameterizes major processes in terms of simple power laws. For instance, the collection rate is represented by

$$\left(\frac{\partial r_r}{\partial t}\right)_{\mathrm{coll}} \propto r_c^{1.15} r_r^{1.15}. \quad (2)$$

The simplicity of the power law form has the advantage of being analytically integrable.

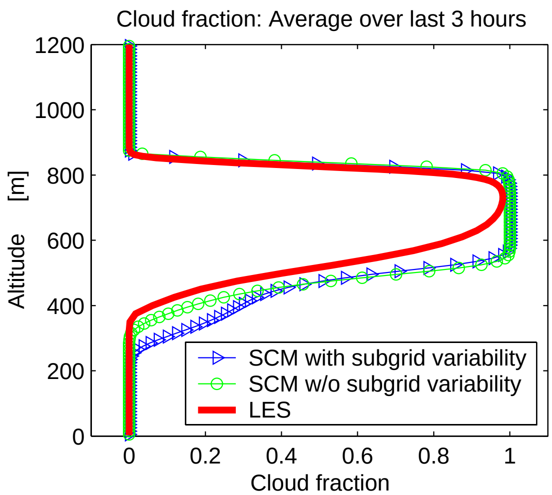

Figure 1: Profiles of cloud fraction averaged over the last 3 hours of the DYCOMS-II RF02 marine stratocumulus simulations. Plotted are the standard SCM profile (blue triangles), the SCM with horizontally averaged fields fed into the microphysics (green circles), and a three-dimensional LES (thick red line). The standard SCM produces a spurious cumulus layer under the (overcast) stratocumulus cloud, unlike the LES.

2. CASE SET-UP: A DRIZZLING MARINE STRATOCUMULUS SIMULATION

We have implemented the KK microphysics, integrated analytically over a Gaussian-mixture/lognormal PDF, in our SCM. We specify cloud droplet number concentration (N_c) and variance ($\overline{N_c'^2}$). We use this model to simulate drizzling nocturnal marine stratocumulus observed during flight RF02 of the DYCOMS-II field experiment (Stevens and Co-authors 2003). This simulation was set up according to the specifications of a recent GCSS model intercomparison (http://www.atmos.washington.edu/~breth/GCSS/GCSS1-RF02-SCM.html). The simulation lasts six hours.

We compare this simulation to two others. First, we run the SCM as above but we input horizontal means into the KK microphysics. This allows us to assess the consequences of ignoring subgrid variability in the forcing of the microphysics. Second, we perform LES of the same GCSS case using the same setup (http://sky.arc.nasa.gov:6996/ack/gcss9/index.html). The LES has a much more sophisticated representation of turbulence and thermodynamic variability than the SCM, but otherwise the two models are similar. Therefore, the SCM can, at best, only emulate the LES, not surpass it. That is, if the SCM matches observed data better than the LES, it is likely only because of luck or tuning. Hence, we use the LES output as "truth" against which to compare the SCM simulations. In reality, most LES in this intercomparison underpredicted observed surface drizzle rates. Investigating the causes of this, e.g. a lack of mesoscale organization or inaccurate microphysics schemes, is beyond the scope of this study.

The LES model used was COAMPS-LES (Golaz et al. 2005). It uses a variant of the KK microphysics in which the coefficient of evaporation, C_{evap}, is a factor of 3 less than ours (a significant change), and in which the radius of newly formed drizzle drops is 28 microns instead of 25 microns (a less significant change). The LES uses a horizontal grid spacing of 50 m and a stretched vertical grid spacing that is as fine as 5 m near the ocean surface and atmospheric inversion. The domain size is $6.4 \times 6.4 \times 1.5$ km.

3. SCM AND LES SIMULATIONS

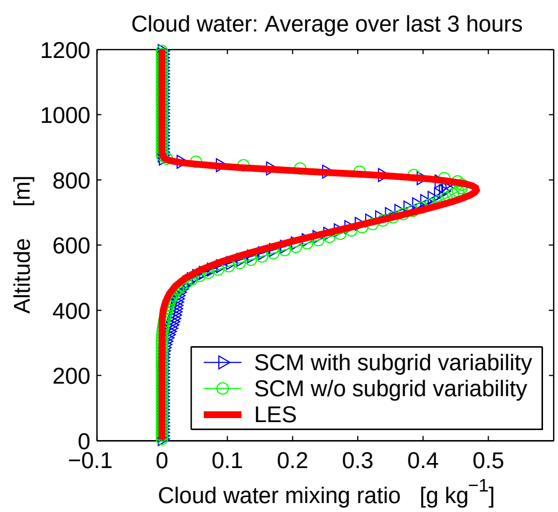

Figure 2: Profiles of cloud water mixing ratio averaged over the last 3 hours of the DYCOMS-II RF02 marine stratocumulus simulations. Plotted are the standard SCM profile (blue triangles), the SCM with horizontally averaged fields fed into the microphysics (green circles), and a three-dimensional LES (thick red line). All three simulations show close agreement.

We now compare profiles from 1) the standard SCM simulation, in which horizontal variability is used to force the microphysics (blue triangles); 2) the SCM simulation in which *horizontally averaged* fields are fed into the microphysics (green circles); and 3) the COAMPS-LES (thick red line).

Cloud fraction is shown in Fig. 1. All three simulations produce an overcast stratocumulus layer, as observed, but the standard SCM (with subgrid variability) produces a small, spurious cumulus layer under the stratocumulus. In this respect, the standard SCM actually performs worse than when variability is ignored. The spurious moisture is related to excessive evaporation below the stratocumulus layer. All three simulations produce comparable cloud water profiles (Fig. 2).

The drizzle mixing ratio is plotted in Fig. 3. Compared to the LES profiles, both SCM profiles have more drizzle water near cloud base and less near the ocean surface. This is related to the fact that more evaporation occurs in the SCM simulations, in part because they use a larger coefficient of evaporation. Turning off subgrid forcing of microphysics in the SCM causes less drizzle to form.

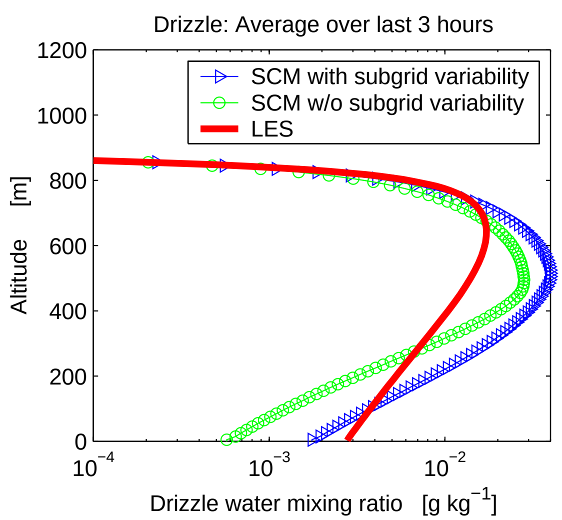

Figure 3: Profiles of drizzle water mixing ratio averaged over the last 3 hours of the DYCOMS-II RF02 marine stratocumulus simulations. Plotted are the standard SCM profile (blue triangles), the SCM with horizontally averaged fields fed into the microphysics (green circles), and a three-dimensional LES (thick red line). Compared to LES, both SCM profiles simulate more drizzle near cloud base and less drizzle at the ocean surface.

The differences in drizzle between the two SCM simulations appear small because of the semilog plot. To highlight the difference, we plot the ratio of r_r in Fig. 4. When subgrid forcing of microphysics is omitted, r_r is lower by about 40% in cloud and a factor of 5 at the ocean surface.

Why does this underprediction in r_r occur? In part, it occurs because without subgrid variability, collection

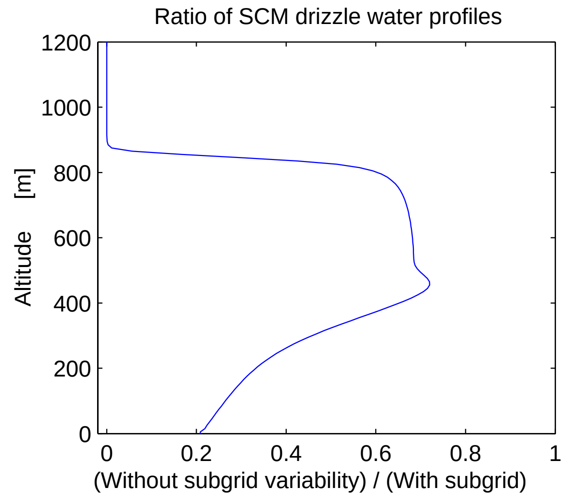

Figure 4: The ratio of the SCM drizzle profiles averaged over the last 3 hours of the DYCOMS-II RF02 marine stratocumulus case. Plotted is [the drizzle mixing ratio produced by the SCM with horizontally averaged fields fed into the microphysics] divided by [the drizzle mixing ratio produced by the standard SCM]. The difference reaches as much as a factor of 5 near the ocean surface.

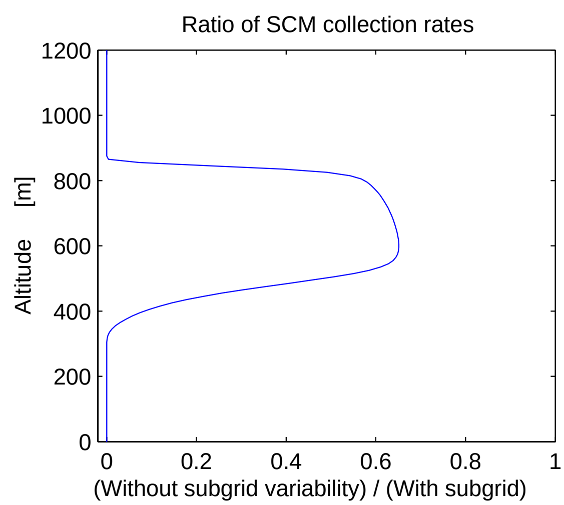

Figure 5: The ratio of the SCM collection rates averaged over the last 3 hours of the DYCOMS-II RF02 marine stratocumulus case. Plotted is [the collection rate produced by the SCM with horizontally averaged fields fed into the microphysics] divided by [the collection rate produced by the standard SCM]. The collection rates differ by 40 to 70% in the cloud layer.

of cloud water by drizzle drops is underpredicted. Cloud water (r_c) and drizzle water (r_r) are positively correlated in the LES of this case. Because of this, the collection rate equation (2) has, effectively, an upward curvature (i.e. is convex) with respect to r_r or r_c. Under this condition, one can show that ignoring subgrid variability leads to a systematic underprediction of collection rate, as shown in Fig. 5 (Larson et al. 2001). The underprediction in collection rate, in turn, leads to an underprediction in drizzle mixing ratio.

4. CONCLUSIONS

This paper has addressed the question of how to couple microphysical processes to cloud fields in a parameterization. As a test case, we have simulated a drizzling marine stratocumulus cloud observed during DYCOMS-II RF02. The simulation was performed in three ways. First, we simulated the cloud using a SCM that employs the assumed PDF method. This method couples the variability in cloud water to variability in drizzle at the subgrid scale. It thereby allows drizzle growth rate to be influenced by the full distribution of cloud water. Crucially, this influence is calculated by integrating *analytically* over the PDF, thereby avoiding the statistical noise and expense of Monte Carlo integration. Second, a further SCM simulation was performed in which the horizontally averaged fields were fed into the microphysical parameterization. This simulation had lower drizzle mixing ratios by a factor of roughly 1.4 within cloud to 5 at the ocean surface. The underprediction occurs because such a simulation omits an important nonlinear effect, namely the effect that a higher drizzle growth rate occurs where cloud water mixing ratio is larger. Third, we performed a LES to serve as a benchmark. The difference in SCM simulations is comparable to differences in drizzle mixing rates produced by different LES models. For instance, the middle 50% of LES models in the DYCOMS-II RF02 intercomparison ensemble produced drizzle mixing ratios that differed by a factor of 10.

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