PARAMETERIZATION OF CLOUD PHYSICS PROCESSES IN MARINE STRATOCUMULUS BASED ON INTEGRAL MOMENTS OF THE DROP SPECTRA

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1. Introduction

One of the main drawbacks of Kessler-type microphysical parameterizations is the difficulty in defining a threshold between cloud and precipitable water. From both theoretical and experimental standpoint this division is artificial since observational and modeling data, in general, do not show distinctive gap between cloud and rainwater. As a result, the autoconversion and accretion rates are quite sensitive to the value of the threshold. The problem is better posed when the artificial division of total water into two parts is avoided altogether (Kogan 1998) and formulation of bulk microphysics is based on full integral moments of cloud drop size distribution (DSD) as opposed to partial moments of Kessler-type parameterizations. Knowledge of six full moments suffices to approximate most of the observed drop size spectra and, hence, the cloud microphysics processes (Belochitski and Kogan 2006). The proposed bulk parameterization is based on five integral moments of the DSD: drop concentration M_0, mean geometrical cross-section of a drop M_2, liquid water content M_3, local drizzle flux M_4 and the radar reflectivity M_6. The mean drop radius M_1, used in calculation of condensation growth rate is parametrized in terms of other moments.

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2. Approach

a. Functional form of the parameterization

System of evolution equations for the chosen set of prognostic variables is given by

$$\frac{\partial M_n}{\partial t} = -\frac{\partial}{\partial x_i}\left(u_i - \delta_{i3}V_n\right)M_n + \left(\frac{\partial M_n}{\partial t}\right)_{cond/evap} + \\ + \left(\frac{\partial M_n}{\partial t}\right)_{activ} + \left(\frac{\partial M_n}{\partial t}\right)_{regen} + \left(\frac{\partial M_n}{\partial t}\right)_{coag} + \\ + \frac{\partial}{\partial x_i}K\frac{\partial M_n}{\partial x_i}, \quad n = 0,2,3,4,6 \tag{1}$$

where u_i is the advection velocity and V_n is the sedimentation rate for the n^{th} moment. The subscripts *activ* and *regen* represent the rate of change of the moment due to CCN activation and regeneration, *coag* and *cond/evap* refer to the, respectively, effects of droplet coagulation and condensation/evaporation.

In order to close the system 1 the unknown sink/source terms are sought as functions of the predicted variables themselves. The general form of the employed expression is given by

$$X = \sum_{i=1}^{n} \alpha_i M_0^{\beta_i} M_2^{\gamma_i} M_3^{\delta_i} M_4^{\epsilon_i} M_6^{\zeta_i}\ , \quad n = 1,2 \tag{2}$$

where X is the parametrized quantity and $\alpha_i, \beta_i, \gamma_i, \delta_i, \epsilon_i, \zeta_i$ are parameters of the fit. The number of addends in the expression 2 depends on the parametrized process.

b. DSD data set

The rates of change of each moment due to various microphysical processes as well as sedimentation rates were calculated using the CIMMS LES model with explicit microphysics (Kogan et al. 1995; Khairoutdinov and Kogan 1999). The role of the model is twofold: first, it serves as a source of the 3D DSD data set; second, it is used as a test bed for comparison of the new bulk parameterization with the benchmark explicit formulation. The DSD database included spectra from the simulation of a marine drizzling cloud layer observed during the ASTEX field experiment on June 12, 1992 (Albrecht et al. 1995). In this experiment, the stratus cloud evolved in a clean air mass. During the six hour long simulation drizzle was gradually increasing, resulting in a breakup of the solid cloud deck and transforming it by the end of simulation into a field of small Cu with cloud cover of about 60%. It should be noted that the explicit model results have been tested against and found in good agreement with integrated observations of microphysical, radiative, and turbulence parameters (Khairoutdinov and Kogan 1999).

The cloud drop spectra database was divided into two parts that corresponded to the two stages of the simulation: the first one representing moderate drizzle (drizzle rates at the surface of 0.2 mm/day) and the second representing heavy drizzle (drizzle rates at the surface of about 1.0 mm/day). Also, each of the parts was subdivided into segments having radar reflectivity Z values, respectively, higher and lower than -9 dBZ. Thus, the database was split up into four parts and separate parameterizations were obtained for each of them. Spectra with liquid water content less than 0.1 g/m^3 were excluded from the consideration since we define the cloud region as having the liquid water content greater than the aforementioned threshold. Also, coagulation was neglected when concentration was lower than 1 cm^{-3}.

c. Nonlinear Regression

The parametrized expressions for moment change rates, fall velocities and the first moment were obtained in the form of the Eq. 2 using the the data set described above and the modified Levenberg-Marquardt method (Dennis and Schnabel 1983). All parameterized expressions have precision better than 30%. This is an improvement in comparison with Kessler-type parameterizations that have precisions of 100% at best.

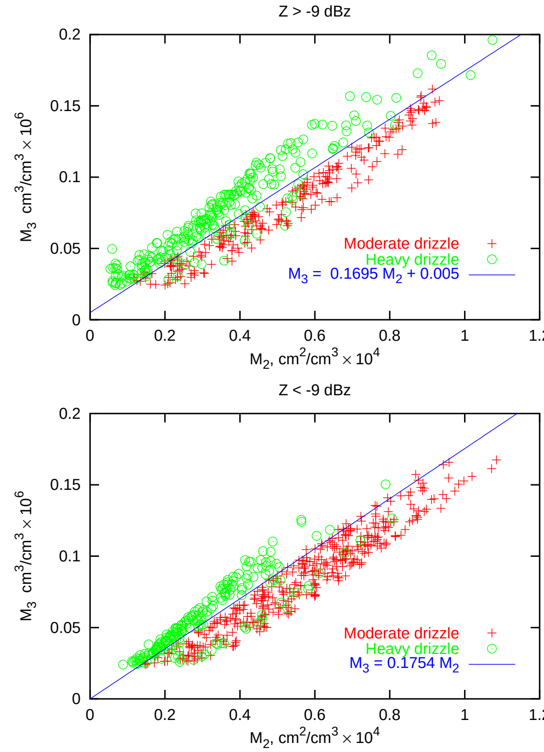

Figure 1: Scatter plots of M_2, $cm^2/cm^3 \times 10^4$, versus M_3, $cm^3/cm^3 \times 10^6$, for moderately and heavily drizzling cloud masses

3. Parameterization of Microphysical Processes

a. Distinction between moderately and heavy drizzling cloud masses

In order to use the parameterization, the means of distinguishing between moderately and heavily drizzling cloud masses have to be established. Scatter plots of M_2 versus M_3 for moderate and heavy drizzle (Fig. 1) show that in the case of $Z > -9\ dBZ$ moments of the spectra of heavily drizzling cloud mass obey the following condition

$$M_3 > 1.695 \times 10^{-4} M_2 + 5 \times 10^{-8} \tag{3}$$

About 90% of the spectra of the aforementioned kind satisfy the above inequality. Also, more than 95% of the spectra of moderately drizzling cloud mass with $Z > -9\ dBZ$ obey the inequality inverse to Eq. 3. A similar expression is obtained for the heavy and moderately drizzling spectra having $Z < -9\ dBZ$.

b. *Coagulation rate*

The *coagulation* process in the new parameterization replaces artificial processes of autoconversion and accretion. The coagulation rate $(\partial M_n/\partial t)_{coag}$ is defined as a change in M_n due to the drop collision and coalescense. The latter process, obviously, does not change the amount of liquid water in the drop population. All parameterizations except one have precisions better or around 20%. The parameterization for the fourth moment, M_4, for the moderately drizzling case with $Z > -9\ dBZ$ has precision of 27%. Figure 2 shows an example of scatter plots of exact versus parametrized coagulation rates for the moderately drizzling spectra with $Z > -9\ dBZ$. About 20% of all data points are shown.

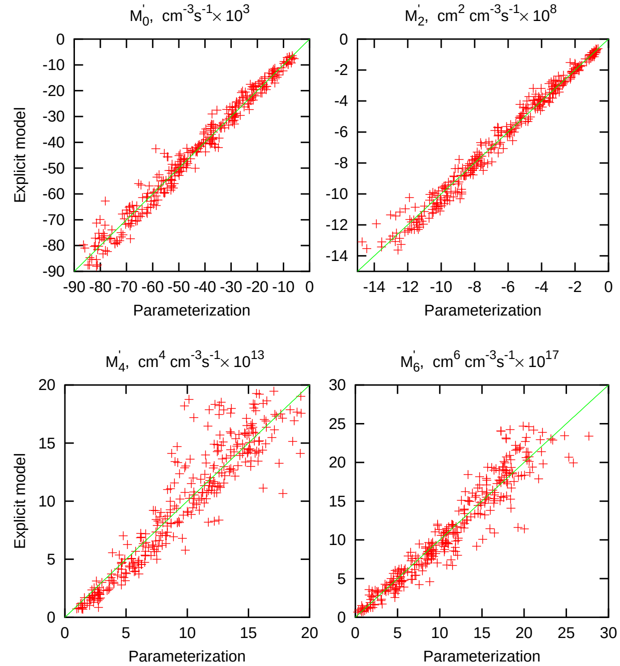

Figure 2: Scatter plots of parametrized values of the coagulation rates M_n', against the explicit model values for the moderately drizzling spectra with $Z > -9\ dBZ$

c. *Sedimentation rate*

Fall velocity of the zero moment, V_0, is of the order of $1\ cm\ s^{-1}$ and, thus, can be safely neglected. Sedimentation rates for all moments are parametrized within about 10% error, except for two parameterizations for M_6, $Z < -9\ dBZ$, which are within 30% error. Figure 3 shows the scatter plots of parametrized values of the of the weighted fall velocity V_n, cm/s, against the values calculated by the explicit model for the moderately drizzling spectra with $Z > -9\ dBZ$.

d. *Condensation and evaporation rates*

It can be shown that the rate of change of n^{th} moment due to condensation/evaporation is given by

$$\left(\frac{\partial M_n}{\partial t}\right)_{cond/evap} = (1 - \delta_{n0})\, nGSM_{n-2} \tag{4}$$

where S is supersaturation, and G is a function of temperature and pressure (see, e.g. Rogers and Yau (1989)). Note, that $(\partial M_0/\partial t)_{cond/evap} = 0$ and $(\partial M_3/\partial t)_{cond/evap}$ is proportional to the first moment. Thus, in order to close the system 4, first moment is parametrized with approximation accuracy of about 5%.

The moist saturation adjustment scheme is used instead of the precise equations 4 whenever any moment, except the third moment M_3, vanishes during the evaporation process. If M_3 becomes zero or negative then all moments are set to zero.

e. *Activation and regeneration rates*

Activation and regeneration processes are parameterized using a variation of Twomey scheme (Twomey 1977).

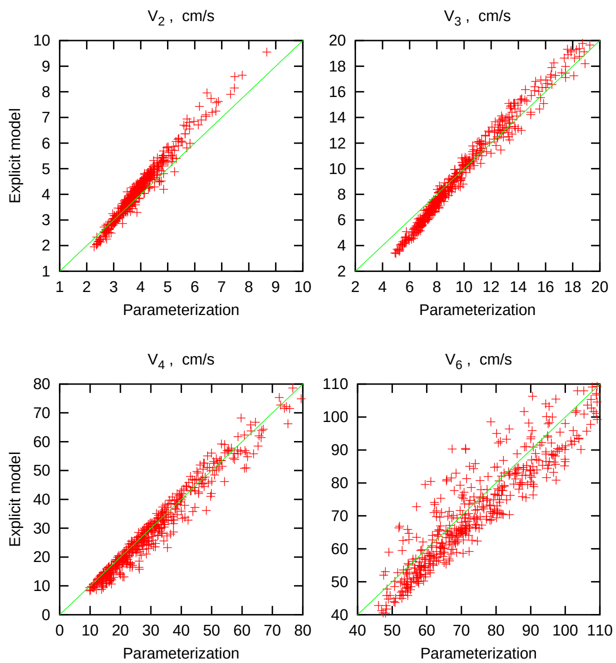

Figure 3: Scatter plots of parametrized values of the weighted fall velocity V_n, cm/s, against the explicit model values for the moderately drizzling spectra with $Z > -9\ dBZ$

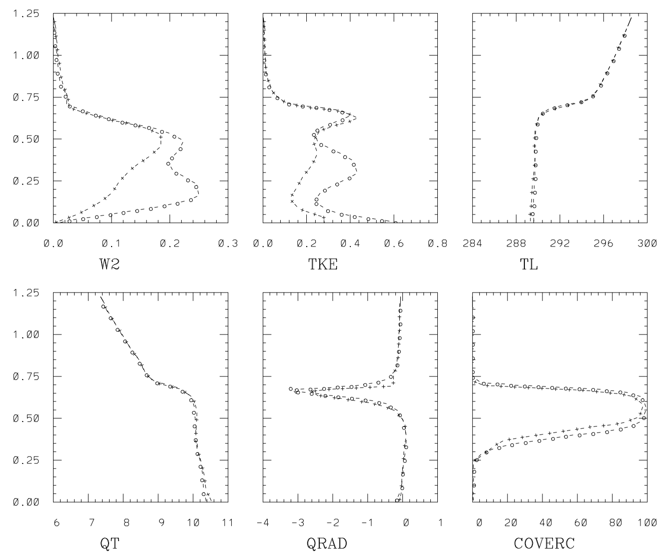

Figure 4: Vertical profiles of vertical velocity ($W2$), m^2, TKE, m^2s^{-2}, liquid water potential temperature (TL), K, total water (QT), $g \times kg^{-1}$, radiation fluxes balance ($QRAD$), Wm^{-2}, and the fractional cloud cover ($COVERC$) for the bulk (circles) and explicit (crosses) simulations

4. Results

a. Initialization of the CIMMS LES model

The parameterizations developed in the previous chapter were incorporated into the CIMMS LES model. The initial thermodynamic soundings were based on the ASTEX A209 flight measurements (Albrecht et al. 1995). The surface pressure was set to $1030\ \ mb$. The initial geostrophic wind profile was set to $(u, v) = (0.0, -10.0)\ \ ms^{-1}$. The values for the heat and moisture surface fluxes were fixed at 0.01 $K \times ms^{-1}$ and $10^{-5}\ g \times cm^{-1}$. The large-scale subsidence divergence was $5 \times 10^{-6}\ s^{-1}$. The numerical domain size was $3 \times 1.25\ km$ with the resolution $(\Delta x,\ \Delta z) = (46.9\ m,\ 25\ m)$. In the bulk model we assumed the power-distribution given by the Twomey formula with the supersaturation threshold 0.2% and fit parameters $C = 49.8$ and $k = 0.22$. The first 40 min of simulations were run using a simple saturation adjustment method to diagnose the cloud water content and with no drizzle allowed. Then, the explicit model was initialized using the liquid water field and setting the drop concentration equal to the total CCN count. The coagulation of drops was delayed for 20 minutes after the start of explicit microphysics. In 60 minutes after the start of coagulation, the new bulk microphysics scheme was initialized using the values of moments produced by the explicit model. Thus, the first two hours were in fact used for the adjustment of the thermodynamical, dynamical and microphysics fields. Each simulation ran with the 4 sec dynamical and 0.2 sec microphysical time steps.

b. Simulation of precipitating stratocumulus-topped boundary layer (STBL)

We will compare the results of the explicit and bulk microphysics simulations of the drizzling STBL. The vertical

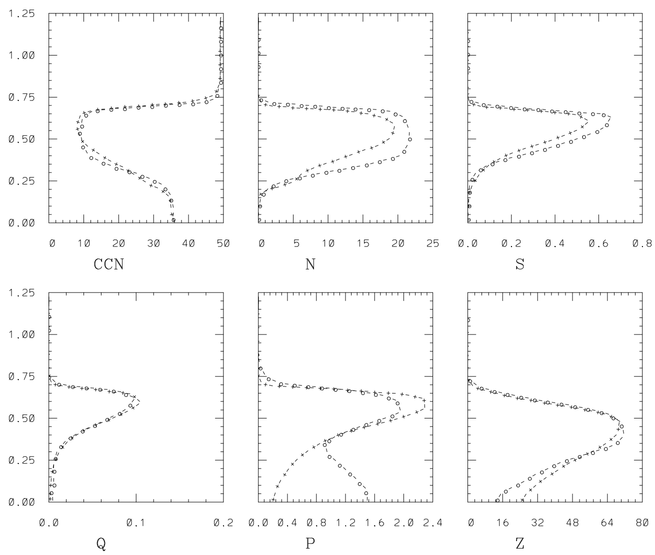

Figure 5: Vertical profiles of the CCN count, cm^{-3}, zero moment (N), cm^{-3}, second moment (S), $cm^2/cm^3 \times 10^4$, third moment (Q), $cm^3/cm^3 \times 10^6$, fourth moment (P), $cm^4/cm^3 \times 10^{10}$, and sixth moment, $cm^6/cm^3 \times 10^{16}$, for the bulk (circles) and explicit (crosses) simulations

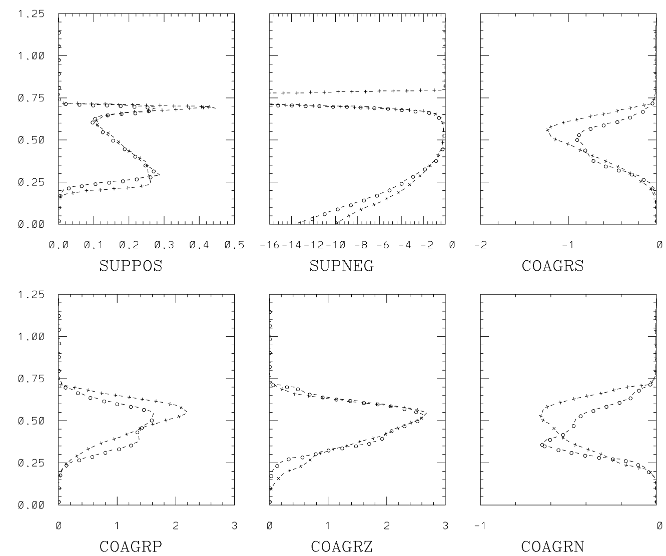

Figure 6: Vertical profiles of the positive supersaturation, %, negative supersaturation, %, rates of coagulation for the second moment ($COAGRS$), $cm^2/cm^3/s \times 10^8$, fourth moment ($COAGRP$), $cm^4/cm^3/s \times 10^{13}$, sixth moment, $cm^6/cm^3/s \times 10^{17}$ and first moment ($COAGRN$), $cm^{-3}s^{-1} \times 10^2$ for the bulk (circles) and explicit (crosses) simulations

profiles of various quantities, shown on figures 4– 6, represent 1-hour time averages after the second hour of the simulations. The qualitative and quantitative agreement between the explicit and bulk simulations is, in general, satisfactory.

The thermodynamic profiles, represented by the virtual liquid water potential temperature, total water content and the liquid water content are well reproduced by the bulk simulation. The vertical velocity and turbulent kinetic energy profiles are predicted also satisfactory by the new approach. The discrepancy in the vertical velocity values may be attributed to the errors in calculation of the evaporated water in the moist saturation adjustment scheme. The agreement in microphysical characteristics such as CCN count and the DSD moments is quite good except for the fourth moment P in the sub-cloud region.

The new approach predicts microphysical parameters of the stratocumulus clouds reasonably well in the most typical parameter range. We believe a refinement of the regression parameters is possible which will increase the accuracy of the parameterization even more and allow its application for cases with much more intense drizzle.

5. Summary

A new bulk microphysical approach specifically designed for application to boundary layer clouds was developed in this study. The new approach employs full integral moments of the droplet size distribution, as opposed to partial moments used in Kessler-type parameterizations. Thus, there us no need to define the threshold between partial moments, such as cloud and precipitable water or cloud and rain drop concentrations.

The rates of change of each moment due to various microphysical processes as well as sedimentation rates were calculated using the explicit microphysical model. Then, the parametrized expressions for moment change rates, fall velocities and the first moment itself were obtained using nonlinear regression analysis. This approach allowed to obtain rather accurate parameterizations of the process rates. All parameterized expressions have precision better than 30%. This is an improvement in comparison with Kessler-type parameterizations that have precisions of 100% at best.

Predictions of the LES model using the new bulk microphysics are compared with the predictions of the explicit microphysics for the case of drizzling STBL. The new approach is shown to predict microphysical parameters of a precipitating cloud in the range characteristic for marine boundary layer stratocumulus.

References

Albrecht, B. A., C. S. Bretherton, D. Jonhson, W. H. Schuberta, and A. S. Frisch: 1995, The Atlantic Stratocumulus Experiment – ASTEX. *Bull. Amer. Meteor. Soc.*, **76**, 889–904.

Belochitski, A. and Y. Kogan: 2006, Relationship between m-mode gamma type cloud drop size distributions and their integral moments. *Eos Trans. AGU, Jt. Assem. Suppl.*, **87(36)**.

Dennis, J. E. and R. B. Schnabel: 1983, *Numerical Methods for Unconstrained Optimization and Nonlinear Equations*. Prentice-Hall, Englewood Cliffs, New Jersey.

Khairoutdinov, M. F. and Y. L. Kogan: 1999, A Large Eddy Simulation model with explicit microphysics: Validation against aircraft observations of a stratocumulus-topped boundary layer. *J. Atmos. Sci.*, **56**, 2115–2131.

Kogan, Y. L.: 1998, Parameterization of cloud physics processes in mesoscale models of stratocumulus cloud layers. *AMS Conference on Cloud Physics*, Everett, WA.

Kogan, Y. L., M. P. Khairoutdinov, D. K. Lilly, Z. N. Kogan, and Q. Liu: 1995, Modeling of stratocumulus cloud layers in a large eddy simulation model with explicit microphysics. *J. Atmos. Sci.*, **52**, 2923–2940.

Rogers, R. R. and M. K. Yau: 1989, *A Short Course in Cloud Physics*. Butterworth-Heinemann, third edition.

Twomey, S.: 1977, The influence of pollution on the short wave albedo of clouds. *J. Atmos. Sci.*, **34**, 1149–1152.