Parameterization of Drop Effective Radius for Drizzling Marine Stratus in Global Circulation Models

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Introduction

The cloud drop effective radius, R_e, is one of the most important parameters in calculations of cloud radiative properties. Numerous formulations of the effective radius have been developed for use in numerical models (see, e.g., review in Gultepe et al. 1996); however, to the best of our knowledge, they all were designed for non-drizzling clouds. The objective of this paper is to derive a parameterization of R_e for precipitating boundary layer clouds. The R_e parameterization is necessarily a function of cloud prognostic variables used in a specific numerical model. To this regard, we note that the majority of current formulations of cloud processes in numerical models are based on partial moments of the drop distribution function: Q_c, cloud water and Q_r, rain water mixing ratios (Kessler 1969). Kogan and Belochitski (2000) argue that a better-posed problem can be formulated based on the total moments of the drop size distributions (DSD). In this paper, we describe R_e parameterizations based on total, as well as partial moments of the DSD. In the latter case, we use the following set of variables: N - total drop concentration, Q - total liquid water content, and Q_r - drizzle liquid water content, while in the former case - radar reflectivity Z is used instead of Q_r. By using multiple nonlinear regression analysis, we seek R_e in the form $(R_e)_{par} = D\, N^A\, Q^B\, Z^C$, where $(R_e)_{par}$ is in microns, Q and Q_r in g m^{-3}, N in cm^{-3}, and Z in dBZ.

Approach and Model

The study was based on microphysical data obtained from simulations made using the Cooperative Institute of Mesoscale Meteorological Studies (CIMMS) large-eddy simulation (LES) model. The model explicitly predicts cloud condensation nucleus (CCN) and DSD functions (Kogan et al. 1995). We simulated the case of a cloud layer observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) field experiment on June 12, 1992. The marine cloud layer evolved in a clean air mass producing moderate (0.2 mm/day) to heavy drizzle (1.0 mm/day) at the surface. The boundary layer was well mixed with a stratocumulus base at 250 m to 300 m and a capping inversion at 700 m to 800 m. Cloud layer parameters evolved quite significantly during the six-hour-long simulation period. Drizzle was gradually increasing, resulting in a breakup of the solid cloud deck and transforming it eventually into a field of small Cu with cloud cover of about 60%. We, therefore, divided the whole simulation into two periods: the first representing a moderate drizzle case (referred to as case M), while the second representing a heavy drizzle case (referred to as case H). Simulations were made in a domain of 3 km × 3 km × 1.25 km using resolution 75 m × 75 m × 25 m, respectively. From each simulation we extracted about 4,000 to 6,000 DSD that comprised the data set used for deriving the parameterization, as well as a benchmark for its verification. Finally, we would like to mention that the simulation results have been tested against and found in good agreement with integrated observations of microphysical, radiative, and turbulence parameters (Khairoutdinov and Kogan 1999).

Two- and Three-Variable Parameterizations of Effective Radius

Martin et al. (1994) using observations of non-drizzling marine clouds obtained a parameterization for R_e in the form $R_{vol}^3 = k\ R_e^3$ where k = 0.8. This expression can also be rewritten as $R_e = 66.7(Q/N)^{1/3}$ (R_e is in microns, Q in g m^{-3}, N in cm^{-3}). As Figure 1 shows, this parameterization performs reasonably well for the moderate drizzle case (root-mean-square [rms] error of 4.7%), but rather poorly for the case of heavy drizzle (rms error of 13%).

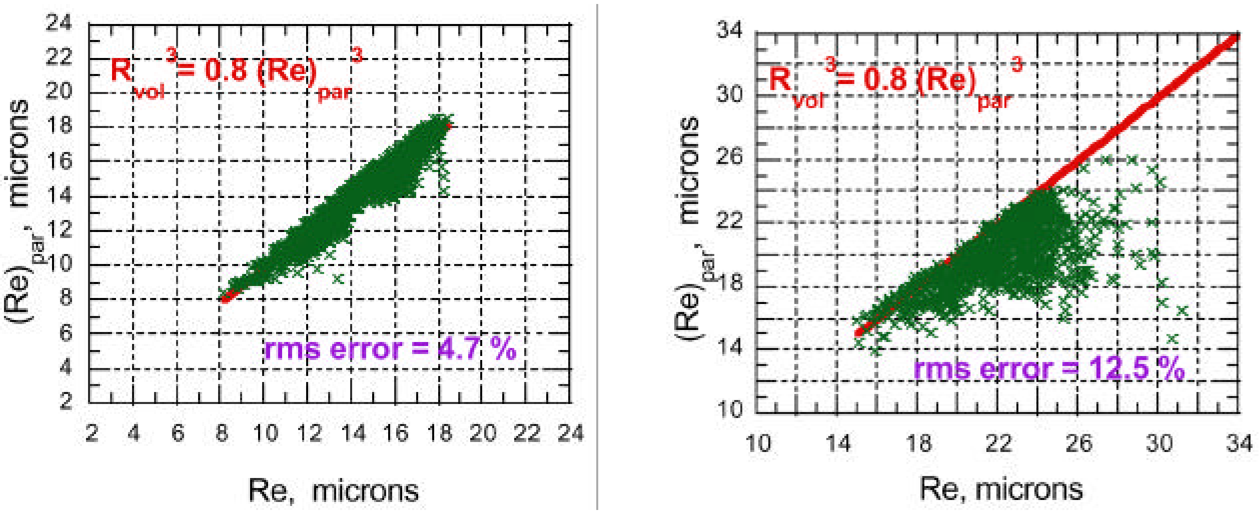

Figure 1. The scatter plots of Martin et al. (1994) $(R_e)_{par}$ versus the benchmark value of R_e from the explicit microphysical model for moderate (left) and severe (right) drizzle.

Using regression analysis, it is possible to find R_e as a more general function of two variables, Q and N, which provides a more accurate two-variable parameterization for R_e (Figure 2). As our regression analysis shows, in this new parameterization the constant k = 0.8 should be replaced by an expression

$$k = 0.57(QN)^{0.15} \quad \text{or} \quad k = 0.95Q^{0.30}N^{-0.03} \tag{1}$$

for the M case or H case, respectively. For values Q and N typical for the moderate drizzle case, $k \approx 0.7$, while for the heavy drizzle case $k \approx 0.5$. Figure 3 shows k as a function of R_e (both averaged in the vertical). Clearly, marine stratus with more drizzle (smaller N or larger R_e) will have a smaller k. Our expression for k is consistent with results observed during the Indian Ocean Experiment (INDOEX) field program. McFarquhar and Heymsfield (2000) report values of k = 0.60 for clean drizzling clouds, while for non-drizzling clouds k = 0.85. In some instances, they observed values of k as low as 0.4 (McFarquhar, personal communication, 2000).

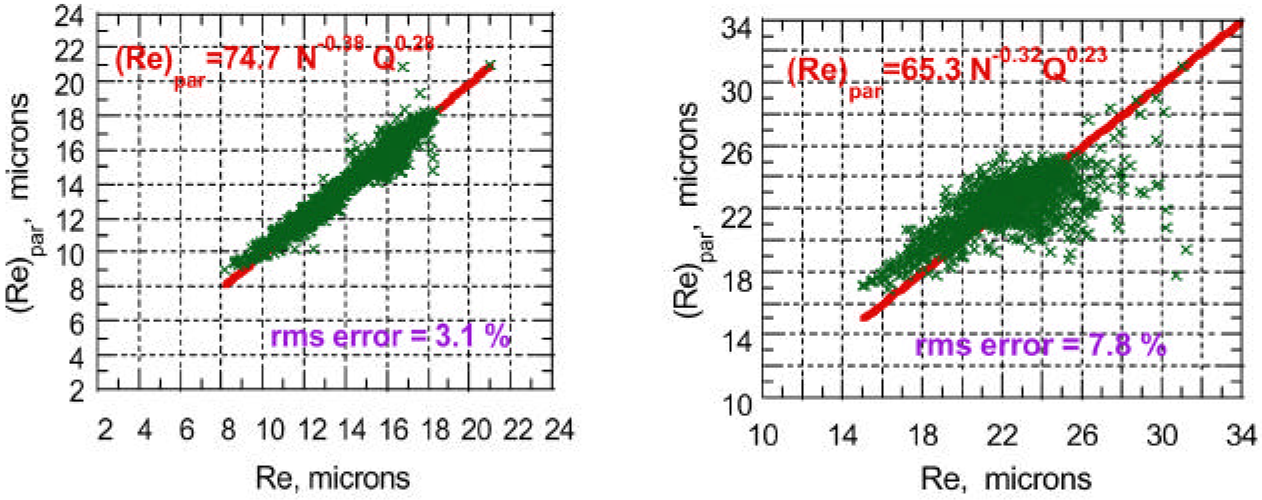

Figure 2. The scatter plots of $(R_e)_{par}$ defined as a function of two variables versus the benchmark value of R_e from the explicit microphysical model for moderate (left) and severe (right) drizzle.

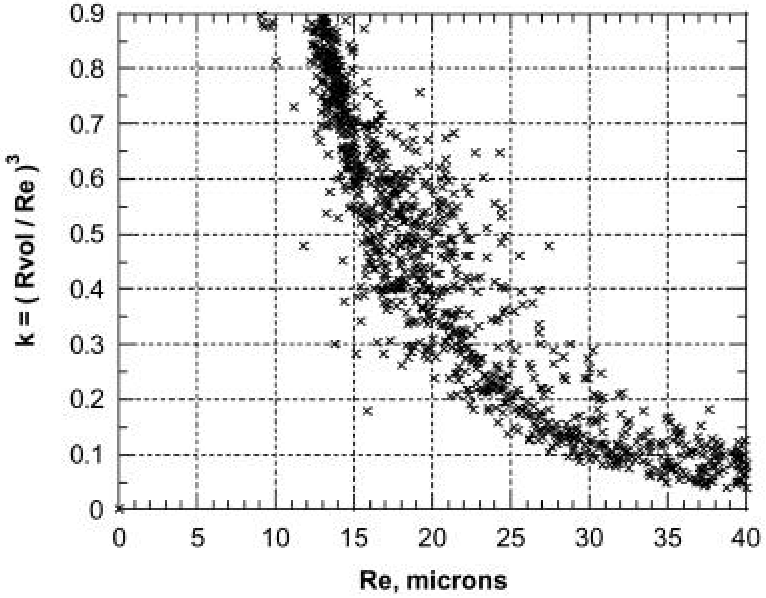

Figure 3. The constant k as a function of effective radius (amount of drizzle).

The Figure 2 results show that the two-variable parameterization performs rather accurately for the M case (rms error of 3.1%), but is still quite inaccurate for the heavy drizzle case (rms error of 7.8%). The accuracy of parameterization can be increased if radar reflectivity factor Z is added as a third variable. Figure 4 shows that the rms error is reduced to 2.6% and 5.1% for the M and H case, respectively. Thus, the three-variable parameterization is much more accurate and can be used for a wide range of ambient conditions characterizing marine drizzling stratocumulus.

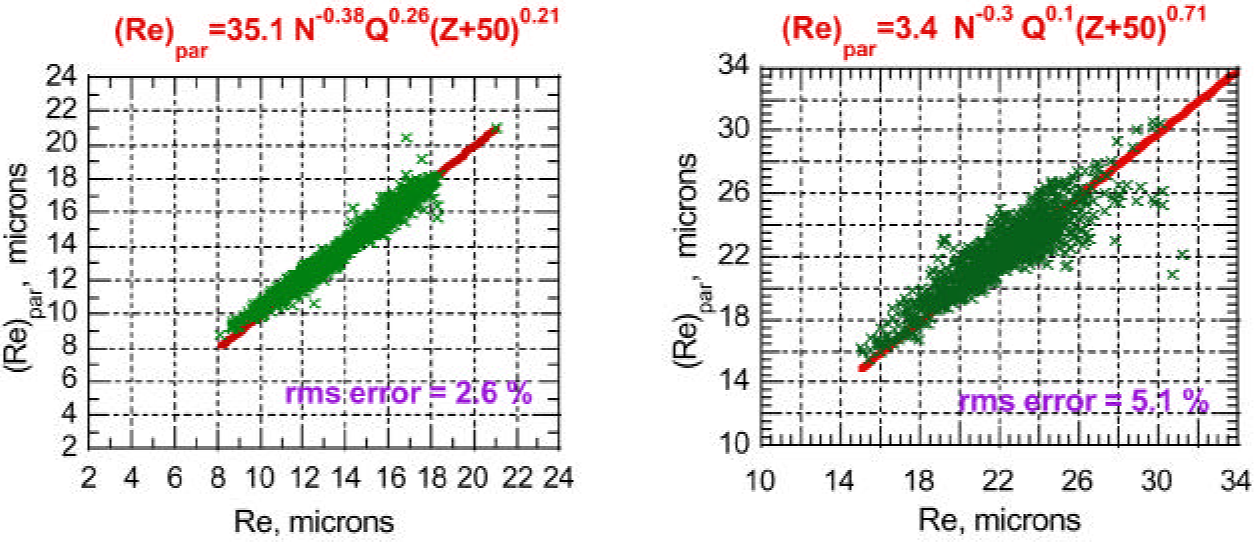

Figure 4. The scatter plots of $(R_e)_{par}$ defined as a function of three variables versus the benchmark value of R_e from the explicit microphysical model for moderate (left) and severe (right) drizzle.

The analysis of the pdf of R_{vol} for M and H cases shows that the condition $R_{vol} > 16.0\ \mu$ is satisfied by 93% of the heavy drizzle data points and 7% of moderate drizzle points. Alternatively, $R_{vol} < 16.0\ \mu$ defines equally well the moderate drizzle case. Thus, the parameterizations derived separately for M and H case can be used in a unified form:

$$(R_e)_{par} = 35.1\ N^{-0.38}\ Q^{0.26}\ (Z+50)^{0.2} \qquad \text{if } R_{vol} < 16.0\ \mu$$

or (2)

$$(R_e)_{par} = 3.4\ N^{-0.3}\ Q^{0.1}\ (Z+50)^{0.71} \qquad \text{if } R_{vol} > 16.0\ \mu$$

where $(R_e)_{par}$ is in microns, Q and ___ in g m^{-3}, N in cm^{-3}, and Z in dBZ. The accuracy of unified parameterization is essentially the same as in the case of separate parameterizations shown in Figure 4.

Finally, we derived an R_e parameterization for a particular threshold radius 32.0μ based on partial moments using drizzle water content instead of radar reflectivity.

$$(R_e)_{par} = 82.4\ N^{-0.38}\ Q^{0.26}\ Q_r^{\ 0.02} \quad \text{or} \quad (R_e)_{par} = 65.1\ N^{-0.27}\ Q^{0.08}\ Q_r^{\ 0.11} \tag{3}$$

for M and H case, respectively. Here $(R_e)_{par}$ is in microns, Q and Q_r in g m^{-3}, N in cm^{-3}. The error of this parameterization depends on the definition of the threshold radius dividing the cloud and drizzle water. The parameterization performs quite well for a particular threshold (32.0μ); however, its performance becomes much worse if we use a different threshold, e.g., 25.4μ or 40.3μ. In the H case, the rms absolute error is 2μ compared to 1.2μ for the total moment parameterization. Thus, the uncertainty in the definition of the threshold radius leads to significantly larger errors in the case of partial moment parameterization.

Conclusions

The microphysical data obtained from the LES model with explicit microphysics was used to derive parameterizations of the effective radius for drizzling marine stratus clouds. It was shown that the three-variable parameterization is the most accurate when it is based on total moments of the drop distribution function (total liquid water, drop concentration, and radar reflectivity) and can be confidently used for the whole range of R_e characterizing moderate to heavy drizzling clouds. The parameterization can be used in a unified form for all drizzle cases employing a separation criteria $R_{vol} \vee 16.0\mu$. The partial moment parameterization is less accurate due to uncertainty in the definition of the threshold radius dividing the cloud and drizzle water.

It was also shown that for light to moderate marine drizzling clouds, the parameterization of Martin et al. (1994) works reasonably well with rms error 4.7%, while in heavy drizzling clouds it significantly underestimates R_e. In heavy drizzle cases, the parameter k relating R_{vol} to R_e depends strongly on radar reflectivity (drizzle water content). It can vary from 0.95 to as low as 0.3. On average, clouds with more drizzle (smaller N and larger Z) will have smaller values of k.

Thus, for moderate to heavy drizzling clouds our results suggest that: (1) the values of k are, in general, smaller than 0.8 ÷ 0.9 values obtained for non-drizzling clouds; (2) k is not a constant, but a function of two to three (depending on drizzle intensity) moments of the DSD function Q, N, and, Z; and (3) there are significant variations of k in the vertical due to increased role of drizzle sedimentation. On average, k increases in the vertical from 0.3 to 0.5 at cloud base to about 0.7 to 0.9 at cloud top. The value of k also depends on drizzle rate. For stronger drizzle (Z > -5 dBZ) the value of k generally falls into a narrower range of 0.6 ÷ 0.3.

Acknowledgments

This research was supported by the Environmental Sciences Division of the U.S. Department of Energy (through Battelle PNR Contract 144880-A-Q1 to the Cooperative Institute for Mesoscale Meteorological Studies) as part of the ARM Program and by the National Science Foundation Grant ATM-9870492. Support for this research was also provided by the ONR Grants N00014-96-1-0687 and N00014-96-1-1112.

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