Parameterization of Drop Effective Radius in Drizzling Marine Stratus for Large-Scale Models

Z. N. Kogan and Y. L. Kogan
Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, Oklahoma

Introduction

Boundary-layer clouds are important components of the earth's energy budget. They cover about 30% of the world's oceans and have high albedos resulting in significant reduction of the shortwave radiation received at the earth's surface. The importance of accurate formulation of radiative parameters of spatially variable clouds as a function of parameters predicted by large-scale models is well understood (see, e.g., Smith 1990). However, at present the representation of boundary clouds in general circulation models (GCMs) is far from adequate. The major problem is that due to large horizontal grid scale and poor vertical resolution, boundary stratus clouds can not be explicitly resolved.

Among the important parameters needed for radiation calculations is the cloud drop effective radius, R_e. For a constant liquid water content Q, the underestimation of R_e results in a corresponding increase of optical depth and, therefore, shortwave cloud reflection. The satellite-derived annually averaged R_e vary from 6 μ to 17 μ, depending on cloud type and location. The 10% relative error in R_e is on average of about 1.5 μ and hardly can be ignored, as follows from the work of Slingo (1990). Based on GCM simulations Slingo showed that a reduction of R_e by 1-2 μ can introduce changes in the earth budget comparable to the global warming effect from doubling CO_2.

At present, the GCMs use a variety of formulations of the effective radius in their calculations of radiative parameters. They range from a simple parameterization which prescribes R_e a constant value (10 μ over the oceans and 5 μ over the land) to formulations which define R_e as a simple function of Q assuming constant cloud drop concentration N (Martin et al. 1994; see also the review in Gultere et al. 1996). All parameterizations used so far were obtained based on data from nondrizzling clouds. To the best of our knowledge, no parameterization exists for the cases of precipitating boundary-layer clouds. The objective of this paper is to derive such parameterization for marine drizzling stratocumulus clouds. We will use data from Large-Eddy Simulation (LES) model with explicit formulation of drop size resolving microphysics. The simulations were based on cases observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) 1992 field campaign.

Approach and Model

The study is based on the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) LES model, which explicitly predicts cloud condensation nuclei (CCN) and drop size distribution functions

(Kogan et al. 1995; Khairoutdinov and Kogan 1999). We simulated the case of a marine stratus cloud layer observed during the ASTEX field experiment on June 12, 1992. It represents a stratus cloud in a clean air mass with light (0.2 mm/day) and moderate drizzle (0.5 mm/day). The observed 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.

Numerical simulations were made in a domain of 3x3x1.25 km using the resolution Δx, Δy, Δz = 75 m, 75 m, 25 m, respectively. From each simulation we extracted about 4,000 drop size distributions that comprised the data set used for deriving the parameterization, as well as a benchmark for its verification. The data set included grid cells within the well-defined cloud layer (300 m to 700 m) with liquid water content exceeding the threshold of $Q_{min} = 0.01$ g/m^3.

Most of the current cloud parameterizations use, at least, two predictive parameters representing partial moments of the drop distribution function: Q_c, cloud water, and Q_r, rain water-mixing ratios (Kessler 1969). A number of large-scale models use the, so called, two-moment parameterization, which includes cloud and rain drop concentration as well. A better posed problem, however, may be formulated based on the total moments of the drop size distribution (Kogan 1998). A parameterization based on this concept is now under development. We are, thus, using the following set of variables describing cloud microstructure: N – total drop concentration, Q – total liquid content, Z – radar reflectivity. As our results show, these variables are sufficient for accurate parameterization of R_e for the case of precipitating stratocumulus cloud layers.

Results

Figure 1 shows the scatter plots of R_e vs Q and Z, respectively, for the cases with combined light and moderate drizzle. The poor correlation between effective radius R_e and Q and Z, as well as N (not shown here) is obvious. Clearly, R_e is a poorly defined function of any single microphysical variable in the case of drizzling stratocumuli.

The next question is: can R_e be determined with sufficient accuracy as a function of two variables? We considered first R_e as a function of Q and Z in the form

$$(R_e)_{par} = C\, Q^A\, (Z+50)^B$$

and secondly as a function of Q and N in the form

$$(Re)_{par} = D\, Q^E\, N^F$$

Here constants A – F are determined from regression analysis using LES data set described above. The constant 50 is added to radar reflectivity Z in order to account for negative values of Z which in our case may be as small as –20 dBZ. The benchmark R_e is calculated from the 3D microphysical field of the drop size distributions.

Figure 2a, b shows the scattergrams of $(Re)_{par}$ vs R_e, where $(R_e)_{par}$ is a function of liquid water content and radar reflectivity for cases of light and combination of light and moderate drizzle. The plots clearly

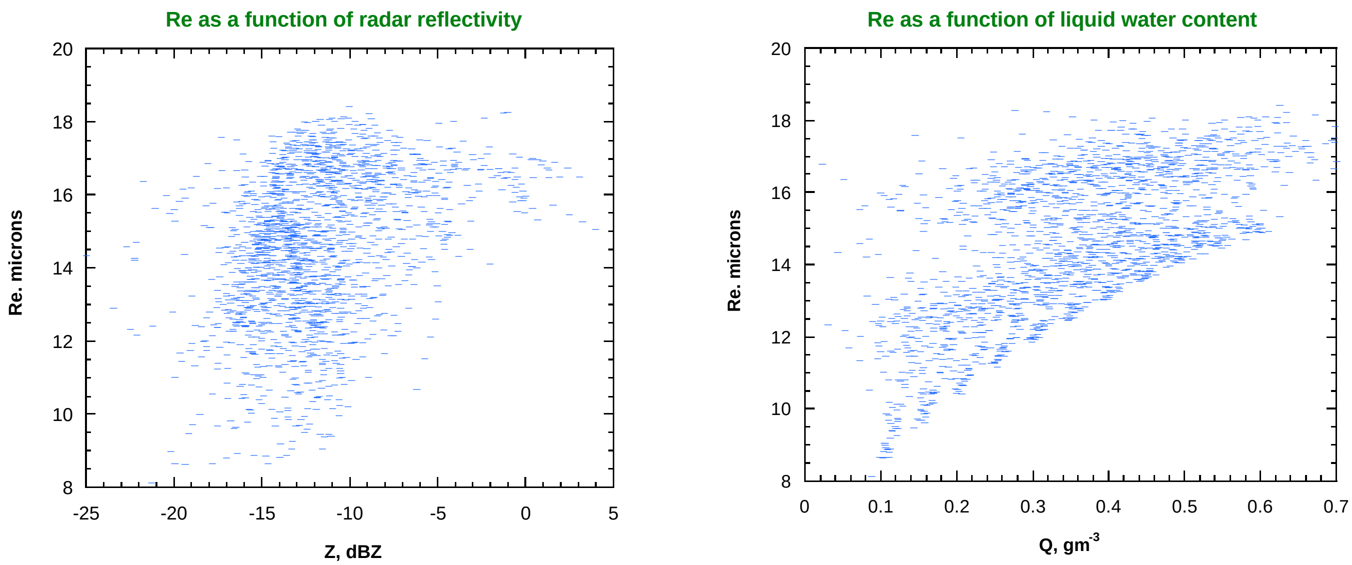

Figure 1. The scatter plots of R_e as a function of: (a) Z and (b) Q.

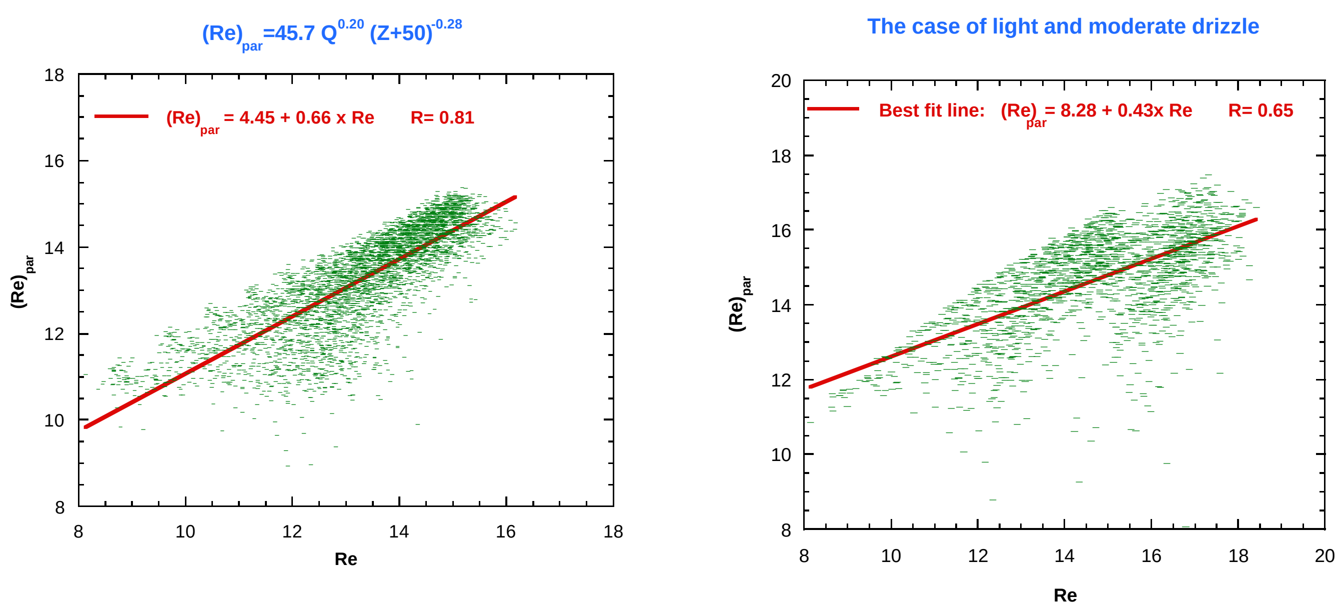

Figure 2. R_e parameterized as a function of Q and Z.

show improvement of the correlation between $(R_e)_{par}$ and R_e, although the scatter is still large, especially for the case of a moderate drizzle.

R_e, however, is a much more accurate function of another two variables, N and Q. This is quite evident from plots shown in Figures 3a and 3b. The expressions (1) and (2) that represent parameterization of $(R_e)_{par}$ for the cases of light and combined light and moderate drizzle, are very close to each other:

$$(R_e)_{par} = 71.0\, Q^{0.27}\, N^{-0.37} \qquad (1)$$

$$(R_e)_{par} = 72.4\, Q^{0.28}\, N^{-0.37} \qquad (2)$$

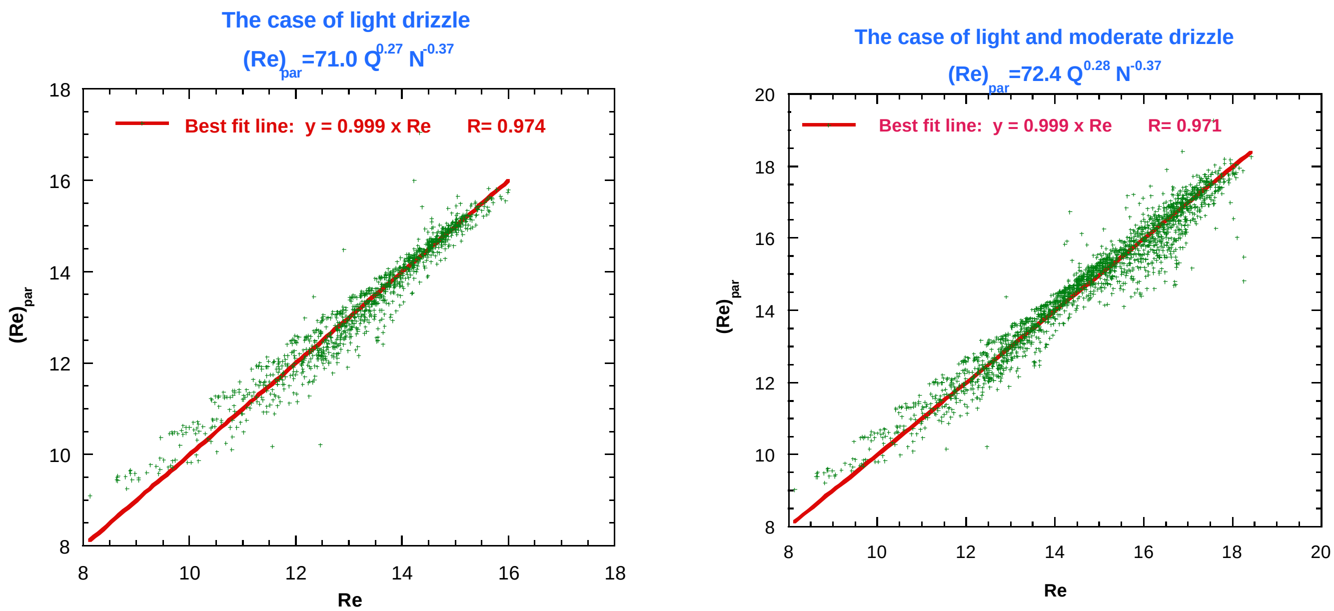

Figure 3. R_e parameterized as a function of Q and N.

The linear best-fit line shows a remarkably good correlation with correlation coefficient R=0.974 and R=0.971 in each of the two cases, respectively. As evident from Figure 3, the two-variable parameterization given by (1) or (2) performs rather well in the wide range of effective radii from 8 μ to 20 μ. The parameterization (2) is only slightly less accurate than (1), however, it covers a wider range of drizzling conditions. The parameterization (2) may also be considered as an expansion of a parameterization derived for non-precipitating clouds and characterized by an effective radius smaller than 8 μ. This parameterization was obtained using airborne observations in marine stratocumulus by Johnson et al. (1992), and by Martin et al. (1994). Martin et al. (1994) parameterization has the form:

$$(R_{vol})^3 = k\, (R_e)^3 \qquad (3)$$

where R_{vol} is a mean volume radius and the constant k is determined empirically, e.g., from airborne observations. Johnson et al. (1992) obtained that for marine non-precipitating stratus $k = 0.81 \pm 0.06$. Martin et al. (1994) using another set of observations found a very close value of $k = 0.8 \pm 0.07$. The expression (3) can be written in the form:

$$(R_e) = 100(3Q)^{1/3} (4\pi\rho k N)^{-1/3} \tag{4}$$

where ρ is the density of liquid water, Q and N are liquid water content and drop concentration, respectively.

Substituting k = 0.8 into (4) yields

$$(R_e)_{par} = 66.7\, Q^{0.33} N^{-0.33} \tag{5}$$

which is rather close to our parameterizations (2). The difference in coefficients A, B, C reflects the drizzle drop spectra present in our data set. Finally, we will consider a parameterization of R_e as a function of three variables N, Q, and (Z+50) in the form

$$(R_e)_{par} = D\, Q^A N^B (Z+50)^C$$

Figure 4 a, b shows that $(R_e)_{par}$ defined as a function of 3 variables has a perfect correlation with the exact value of R_e. The functional are given by the following expression for the case of combined light and moderate drizzle (see also plots in Figure 4):

$$(R_e)_{par} = 33.4 Q^{0.26} N^{-0.37} (Z+50)^{0.21} \tag{5}$$

The correlation coefficient for the best-fit line is 0.982. Clearly, the three-variable parameterization is the most accurate and has the best potential for use in a wide range of ambient conditions characterizing non-precipitating and drizzling marine stratocumulus.

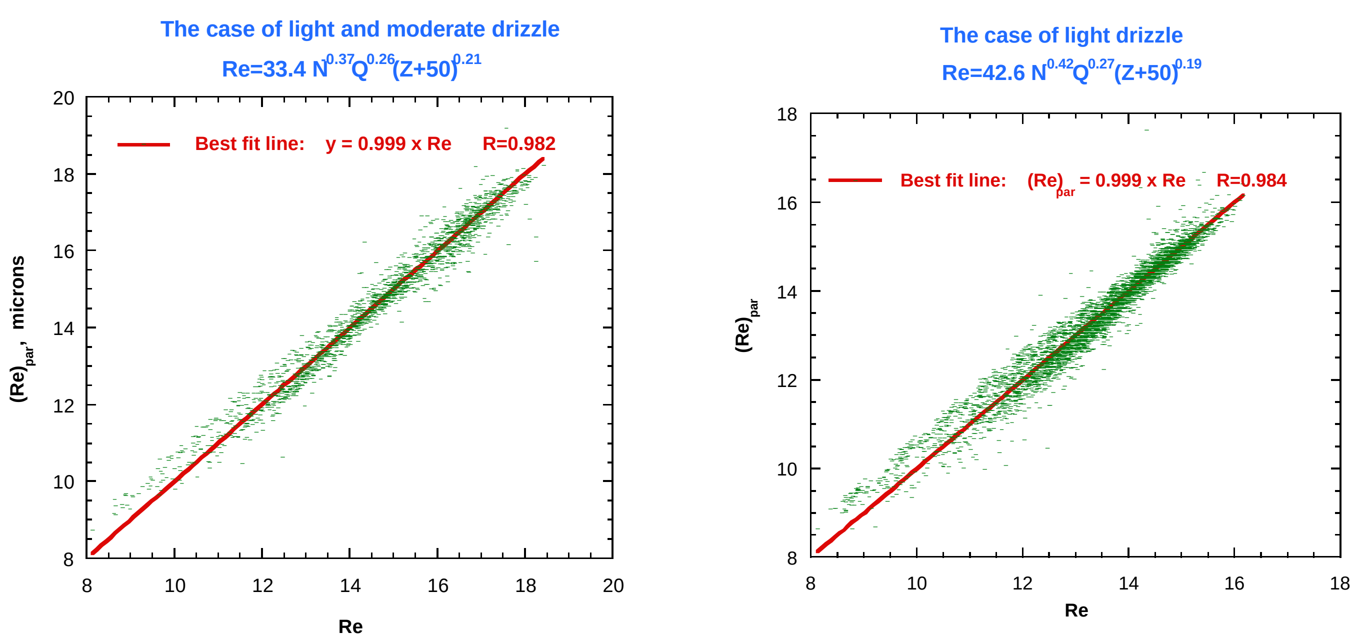

Figure 4. R_e parameterized as a function of Q, N and Z.

Conclusions

The objective of the study was twofold: 1) to determine the minimal set of microphysical parameters required to determine drop effective radius in drizzling stratocumulus clouds and 2) to derive a parameterization for the effective radius with sufficient accuracy. In our investigation, we used data from case studies made using the CIMMS LES model with explicit microphysics. The simulations were based on observations during the ASTEX 1992 field campaign.

It was shown that at least two microphysical variables are needed for accurate determination of R_e in case of drizzling stratocumulus. The use of liquid water content and drop concentration provides an accurate parameterization for R_e in the range of effective radii from 8 μ to 20 μ. The new parameterization given by the expression (2) may be considered as an expansion of a parameterization derived from observations of non-precipitating cloud layers (Johnson et al. 1992; Martin et al. 1994) for the case of drizzling stratocumulus. We have also shown that a three-parameter parameterization based on liquid water content, drop concentration, and radar reflectivity is the most accurate and has the best potential for use in a wide range of ambient conditions characterizing non-precipitating and drizzling marine stratocumulus.

Acknowledgments

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