Evaluation of Two Radiative Parameterizations Using a Three-Dimensional Large-Eddy Simulation Microphysical Model

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Stratocumulus clouds in the marine boundary layer exert a tremendous impact on the planetary radiation balance because of their persistence and large cover (about 25% of the world ocean). Clearly, even relatively small biases in the representation of their radiative parameters, such as optical depth, can produce large errors in the simulated planetary radiation balance. General circulation models (GCM) and climate models most commonly use the following two parameterizations of cloud optical depth. The first employs as input parameters the climatological or in some other way averaged cloud droplet effective radius and liquid water path:

$$\tau_1 = (3/2)\, W/(\rho\, r_{eff}) \qquad (1)$$

where ρ is the water density, r_{eff} is the effective radius defined as the ratio of the third to the second moment of the droplet size distribution function, and W is the liquid water integrated over the cloud vertical layer.

The second parameterization is given as

$$\tau_2 = 2\, \pi\, \bar{r}^{2}\, N_c\, H \qquad (2)$$

where N_c is droplet concentration, $\bar{r}$ is mean droplet radius, and H is the cloud geometrical thickness.

Both parameterizations are obtained from a general theoretical expression for cloud optical depth given according to the formula:

$$\tau_t = \int_0^H \int_0^\infty Q_{ext}(\lambda)\, f\, \pi\, r^2\, dr\, dz \qquad (3)$$

Here f(x,y,z,t,r) is the cloud droplet size distribution function, r radius of a droplet, H is the cloud depth, and Q_{ext} is the extinction efficiency factor for the given wave length λ. For large x ($x=2\pi r/\lambda$) and typical cloud drop-size distributions, Q_{ext} asymptotes approximately to a constant value of 2. As detailed information on cloud drop spectra is not available in large-scale models, parameterizations of optical depth are used instead of (3). Those parameterizations can be obtained by making certain assumptions about averaged micro and macro parameters of the cloud. Thus, in deriving parameterization (2), it is assumed that clouds are spatially homogeneous and all variables are constants averaged over the vertical column corresponding to a grid cell in a large-scale model.

In this paper we will contrast parameterizations (1) and (2) with the general theoretical definition (3), using a set of cloud drop distribution functions generated by the CIMMS three-dimensional (3D) large-eddy simulation (LES) stratocumulus cloud microphysical model (Kogan et al. 1992). The dynamical framework of the CIMMS model is based on the 3D LES code developed by Moeng (1984). The cloud physics formulation follows that of Kogan (1991) and includes explicit formulation of the processes of nucleation, condensation, evaporation, and coalescence based on two distribution functions: one for cloud condensation nuclei and another one for cloud drops. The subgrid-scale eddies are parameterized through Deardorff's (1980) turbulence energy closure model, and the longwave radiation is parameterized according to Herman and Goody (1976).

The input parameters needed to evaluate parameterizations (1) and (2) and contrast them with the exact formula (3) include at least 22 size categories representing the droplet spectrum at each vertical level. Even a very coarse investigation using 10 divisions for each of these variables results in 10^{22} mathematically possible combinations of the input parameters, making the consideration of each of these combinations intractable.

The practical way to obtain a reduced subset of parameter combinations typical for realistic atmospheric conditions is to use the output from cloud model simulations *as a generator of input parameters* needed in (1), (2), and (3). For this purpose, we employed the data from the CIMMS explicit microphysical stratocumulus cloud model.

From each cloud simulation and at each particular time of boundary layer evolution, we extracted about 1600 vertical profiles of cloud drop spectra. Drop spectra in these vertical columns were considered as samples of microphysical data formed under a wide range of dynamical parameters that exist at various spatial locations of the cloud layer. At each of these 1600 combinations of input parameters, we concurrently calculated an exact optical depth according to (3) and parameterized optical depth given by expressions (1) and (2).

The results of the comparison are presented as scatter diagrams in Figures 1 and 2. The comparison results are shown for two simulations that differ only in the initial cloud condensation nucleus (CCN) distribution: the first was characteristic of extremely clean maritime conditions and was initialized with CCN spectrum with total count of 25 cm^{-3} (Woodcock 1957). A more polluted marine atmosphere was simulated in the second case that was initialized with Warner's (1969) CCN spectrum of total count of 328 cm^{-3}.

In each simulation, the cloud-topped boundary layer evolves from cumulus to stratiform regime. During the cumulus stage, the boundary layer is characterized by the predominance of mostly individual small cumulus cloud elements, while at the stratiform stage, it is topped by a continuous deck of stratiforrn clouds.

At the earlier stage of cloud development when the cloud layer is formed mostly by small isolated nonprecipitating cumuli, the scatter for both parameterizations is rather small (Figure 1). The small scatter is due to the fact that cloud drop spectra are predominantly unimodal and narrow. Therefore the representation of these approximately monodispersal spectra by their average values works rather well. Parameterization (1) produces more accurate results than parameterization (2), which underestimates the exact solution.

At the later stage (T=6000 s), when the cloud layer is a solid stratiform deck, parameterization (2) produces very inaccurate results. The inaccuracy is especially evident in the case of small CCN count when coagulation is much more effective and results in a variety of cloud drop spectral shapes (see Figure 2). For the case with larger CCN count (Figure 2, bottom), the scatter is smaller, as spectra are less diverse because of the smaller role of coagulation. However, the results are still rather inaccurate, and, in general, parameterization (2) significantly underestimates the exact solution.

As can be seen from Figure 2, parameterization (1), which employs as parameters the liquid water path and the effective radius, produces much better results than parameterization (2). Again, the scatter is larger in the case of small CCN count, evidently indicating much more complex microstructure in this case.

We conclude that parameterization (1), which is based on the liquid water path and the cloud droplet effective radius as parameters provides the most accurate results in cases of nonprecipitating cloud layers.

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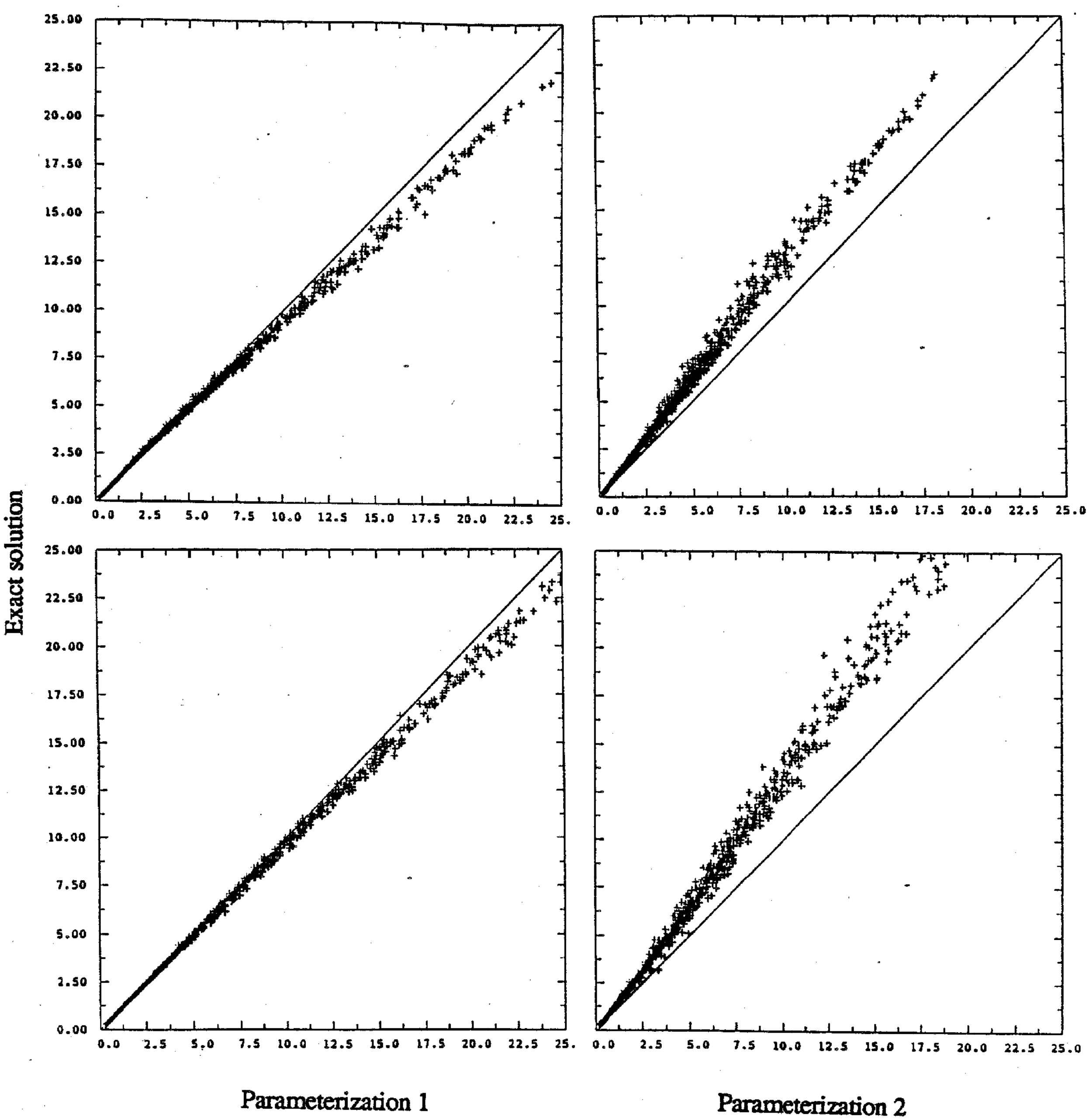

Figure 1. The scatter diagram comparing parameterizations (1) and (2) with the exact formula (3). The top panels are for the case with CCN count of 25 cm^{-3}; the bottom panels are for the case with CCN count 328 cm^{-3}, T=1200 s.

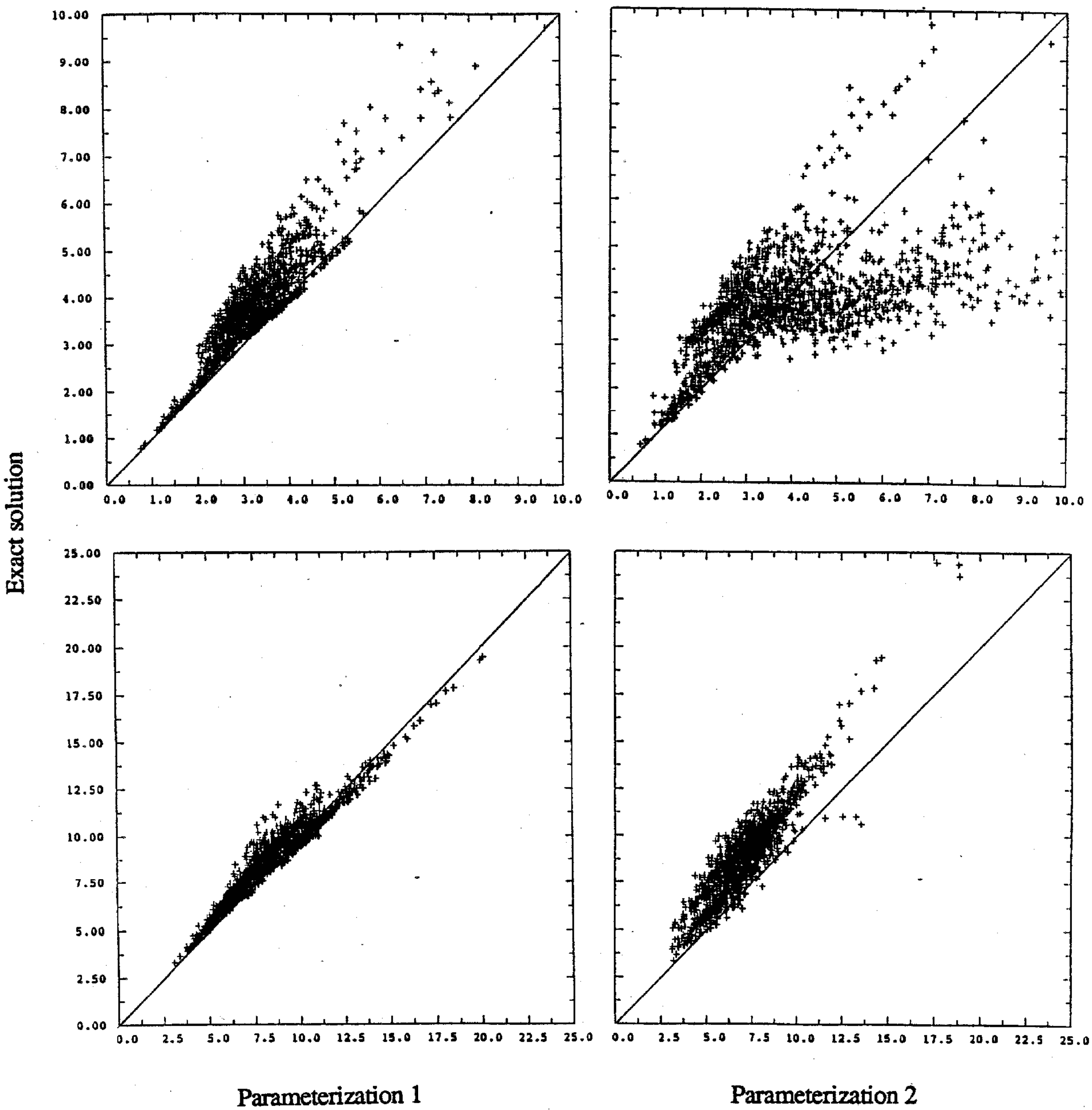

Figure 2. The same as Figure 1, except for T=6000 s.