P1.64 COMPARISON OF BULK AND BIN WARM RAIN MICROPHYSICS MODELS USING A KINEMATIC FRAMEWORK

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1. Introduction

Clouds and their impact on the transfer of solar (shortwave) and thermal (longwave) radiation are the most challenging aspect of climate and climate change (e.g., Stephens 2005 and references therein). One of the most uncertain aspects is the indirect effect of atmospheric aerosols. The indirect impact of aerosols on climate concerns the influence through cloud processes and is traditionally associated with two effects: the impact of changes in droplet size on the optical depth (the first effect; Twomey 1974), and the impact of changes in liquid water path, cloud lifetime, and extent (second effect; e.g., Albrecht 1989). A major source of difficulty in assessing the indirect aerosol effect using GCMs is that they must rely on sub-grid parameterizations to represent clouds and cloud processes, convection in particular. As discussed by Grabowski (2006), these issues can be studied with better confidence using models that are able to resolve convective-scale and mesoscale processes (e.g., cloud-resolving models, CRMs).

Most CRMs rely on bulk cloud microphysics schemes. As far as the indirect effects are concern, these schemes must parameterize the droplet effective radius and coalescence rate (including drizzle/rain formation) using some functional form of the particle size distributions. Bin-resolving microphysics models, on the other hand, explicitly calculate the particle size distribution and therefore provide more rigorous solutions than bulk models. However, computational cost associated with bin microphysics is significantly higher than bulk schemes. It follows that bulk microphysics schemes are currently the only viable approach for many applications, the cloud-resolving approach in particular.

In this study, a new two-moment warm-rain bulk microphysics scheme is developed and tested against a bin microphysics model. Simulations are run for both polluted and pristine aerosol regimes to gauge the ability of the bulk model to simulate indirect the aerosol effects, using the bin model results as a benchmark. Two-moment bulk schemes predict the number concentration and mixing ratio of the hydrometeor species, which increases the degrees of freedom and improves representation of the microphysical processes compared to simpler one-moment schemes (i.e. predicting mixing ratio only). The prediction of cloud particle number concentration and explicit treatment of droplet activation from a distribution of aerosol in a two-moment scheme can potentially provide more physically-robust estimates of the indirect aerosol effect than allowed using simpler schemes (see discussion in Grabowski 2006).

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2. Model description

The new two-moment bulk scheme predicts the number concentrations (N_c, N_r) and mixing ratios (q_c, q_r) of cloud droplets (subscript c) and drizzle/rain (subscript r). Cloud droplets are assumed to follow a gamma size distribution with the spectral width specified as a function of N_c from the observations of Martin et al. (1994). Drizzle/rain is assumed to follow an exponential size distribution. The evolution of number concentration and mixing ratio is determined by a number of microphysical processes: droplet activation of cloud condensation nuclei (CCN), condensation/evaporation, and coalescence processes (autoconversion, accretion, self-collection). Coalescence processes are simulated by either Beheng (1994; B1994), Khrairoutdinov and Kogan (2000; KK2000), or Seifert and Beheng (2001; SB2001). These different parameterizations are tested against the bin model results. Droplet activation is calculated by applying Kohler theory to an assumed lognormal distribution of partially soluble aerosols. Herein, the supersaturation needed for droplet activation and condensation/evaporation calculations is explicitly predicted, as oppossed to most bulk schemes that assume instantaneous adjustment to saturation.

The bin microphysics scheme solves equations for the spectral density function including microphysical processes of droplet activation, condensation/evaporation, and collision coalescence. Collision-coalescence is calculated using the Linear Flux Method (Bott 1998), with collection efficiencies a function of drop size using the tabulated values of Hall (1980 and references therein). Terminal particle fallspeeds, ventilation effects, and droplet activation are the same as the bulk model for consistency.

The bin and bulk microphysics schemes were implemented in a 2D kinematic modeling framework with a specified flow field. The kinematic framework allows for testing of schemes without added complications due to dynamical-microphysical feedbacks, yet it includes the important processes of advective and gravitational transport. Two quasi-idealized cases are presented here: 1) boundary-layer stratocumulus and 2) shallow cumulus. In addition, two aerosol regimes are simulated for each case: POLLUTED and PRISTINE. The total aerosol concentrations for POLLUTED and PRISTINE are 1000 and 100 cm^{-3}, respectively. The soluble portion of the aerosol is ammonium sulfate, with a soluble fraction of 0.9.

For the stratocumulus case, the grid spacing is 20 m in the vertical and horizontal, with a domain size that is 2 km and 1 km deep. The flow field is time-invariant and consists of a single eddy spanning the depth of the domain, with a maximum vertical velocity of $\sim$ 1.7 m/s. A large-scale moisture flux (latent heat flux, or LHF) into the domain equivalent to either 3 W m^{-2} or 30 W m^{-2} is applied evenly to the water vapor mixing ratio field at each time step. Note that in equilibrium values of LHF of 3 W m^{-2} and 30 W m^{-2} correspond to a precipitation rate of about 0.1 and 1 mm day^{-1}, respectively. Simulations are run to the point of near-equilibrium, generally requiring a time integration of about 6 to 12 hours. The specific forcing applied in the stratocumulus case results in a strong link between microphysical processes and macroscopic characteristics of a simulated cloud. In essence, the quasi-equilibrium cloud has to be sufficiently deep to provide precipitation rate balancing the prescribed LHF forcing. For instance, the PRISTINE cloud is anticipated to be shallower than the POLLUTED cloud (i.e., featuring higher cloud base as the cloud top is prescribed by the depth of the domain).

For the case of shallow cumulus, the flow field varies in time representing the development of a shallow convective plume (Szumowski et al. 1998). Initial thermodynamic profiles are based on aircraft data from August 10, 1990 during the Hawaiian Rainband Project (HaRP) (Szumowski et al. 1998). The horizontal and vertical grid spacing is 50 m, over a domain that is 9 km wide and 3 km deep. The flow pattern consists of low-level convergence, upperlevel divergence, and a narrow updraft in the center of the domain. The updraft is held constant at 1 m s^{-1} for the first 15 min, intensifies to a peak value of 8 m s^{-1} at 25 min, later decays to a value of 2 m s^{-1} at 40 min, and is held constant for the remainder of the 60 min simulation.

2. Results

a. Stratocumulus regime.

All simulations are initialized with zero rain water, but after coalescence begins the precipitation rate eventually balances the influx of water specified through LHF and the simulations attain near-equilibrium. The bin and bulk models produce similar results, particularly using the KK2000 and SB2001 collision-coalescence parameterizations in the bulk model. At equilibrium, q_c increases with height while N_c is fairly constant through the depth of the cloud (Fig. 1). This structure is consistent with observations of marine stratocumulus (e.g., Wood 2005). The domain-average equilibrium cloud depth, cloud optical depth, mean ("effective") effective radius $\overline{r}_e$, cloud water path CWP (vertical integral of cloud water content), and droplet concentration N_c for the various simulations are compared in Table 1. The effective $\overline{r}_e$, essentially the value of effective radius needed to produce the correct cloud optical depth for a given CWP, is defined following Grabowski (2006). It has to be stressed that CWP, $\overline{r}_e$, and τ_c are calculated independently for each model column and subsequently averaged over all columns.

Both the bulk and bin simulations exhibit significant differences between the PRISTINE and POLLUTED runs in terms of the cloud depth, CWP, $\overline{r}_e$, and N_c; see Table 1. The bulk simulations produce a decrease in $\overline{r}_e$ between the PRISTINE and POLLUTED runs (the first indirect effect) of 3.4 to 4.1 μm, while the bin model produces a somewhat larger decrease of 5.1 μm. The relative increase in CWP between the bulk PRISTINE and POLLUTED simulations (second indirect effect) ranges from 50% to 96%. The bin model produces an increase of 37%. These changes in CWP correspond primarily to an increase in the cloud depth (i.e., lowering of the cloud base height) allowing for more accretional growth of falling rain so that the surface rain rate balances the influx of moisture through LHF. Overall, the KK2000 scheme produces results closest to the bin model in terms of both the change in CWP and change in $\overline{r}_e$. This finding is perhaps not surprising, given that KK2000 was developed in the context of boundary layer stratocumulus.

The mean rain drop size has a strong impact on the equilibrium cloud characteristics produced by the bulk model, which has implications for most bulk microphysics schemes which predict only one moment for rain water (i.e., schemes that predict rain mixing ratio but not number concentration). These schemes typically specify a constant intercept parameter N_0, and then diagnose the mean rain drop size from q_r and N_0. In two-moment schemes, N_0 and mean rain drop size are free parameters that vary with the predicted N_r and q_r. Using the two-moment scheme here, N_0 varies widely (over four orders of magnitude) across the domain for a given simulation (see Figure 2). To test the impact of N_0, we have modified the bulk scheme to predict only one moment (mixing ratio) for rain. The equilibrium cloud microphysics are highly sensitive to the specification of N_0 using the one-moment scheme. Increasing N_0 means that the mean rain drop size is decreased for a given q_r, resulting in slower sedimentation and more evaporation. Thus, a deeper cloud layer, more cloud water, and reduced autoconversion and accretion rates are needed to produce the same surface precipitation rate to balance LHF as required by equilibrium. Using a value of N_0 of 10^7 m^{-4}

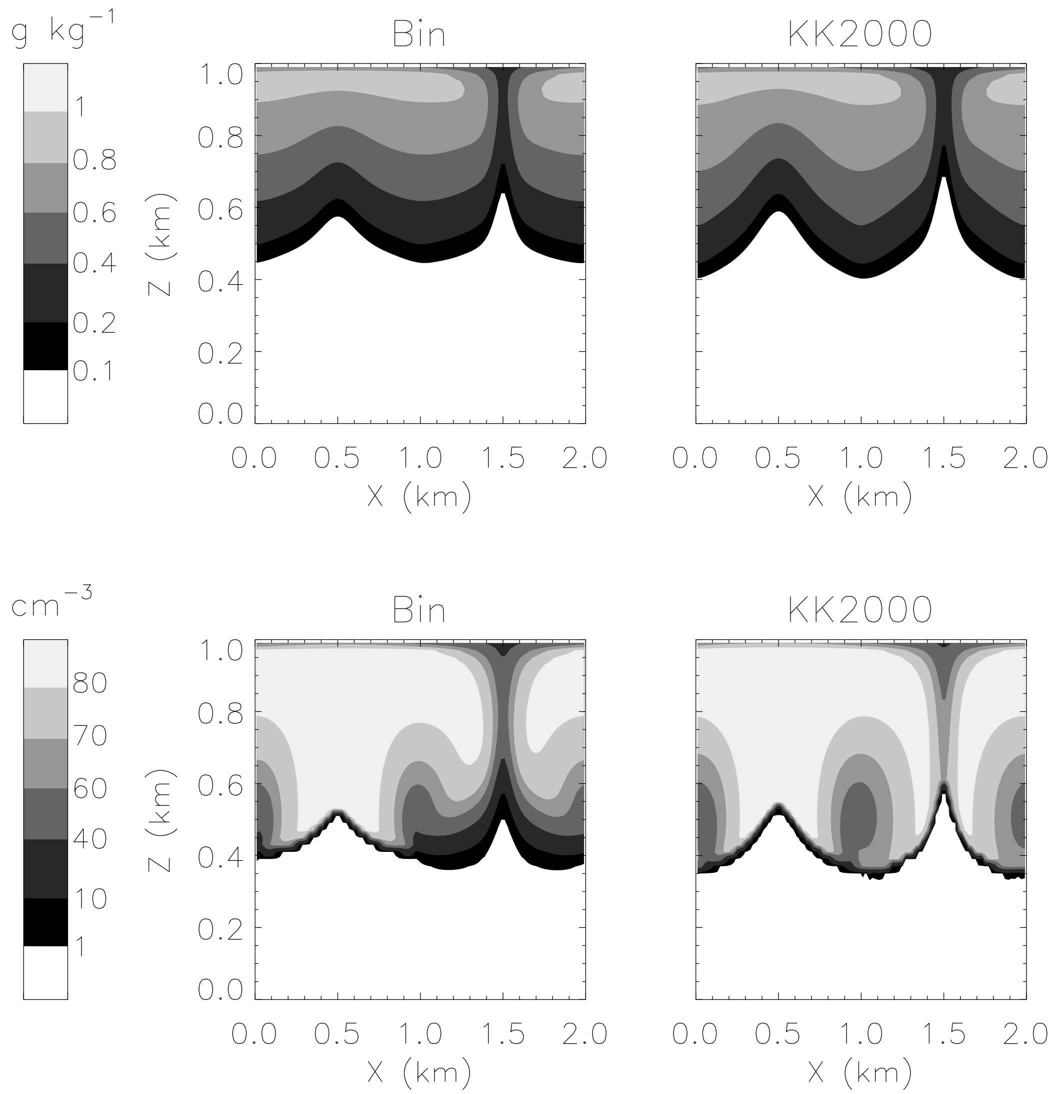

Figure 1: X-Z plot of the equilibrium cloud water mixing ratio (top panel) and droplet number concentration (bottom panel), for the bin and bulk (using KK2000) PRISTINE stratocumulus simulations. A similar cloud structure (but with greater water content and droplet concentration) is produced for POLLUTED.

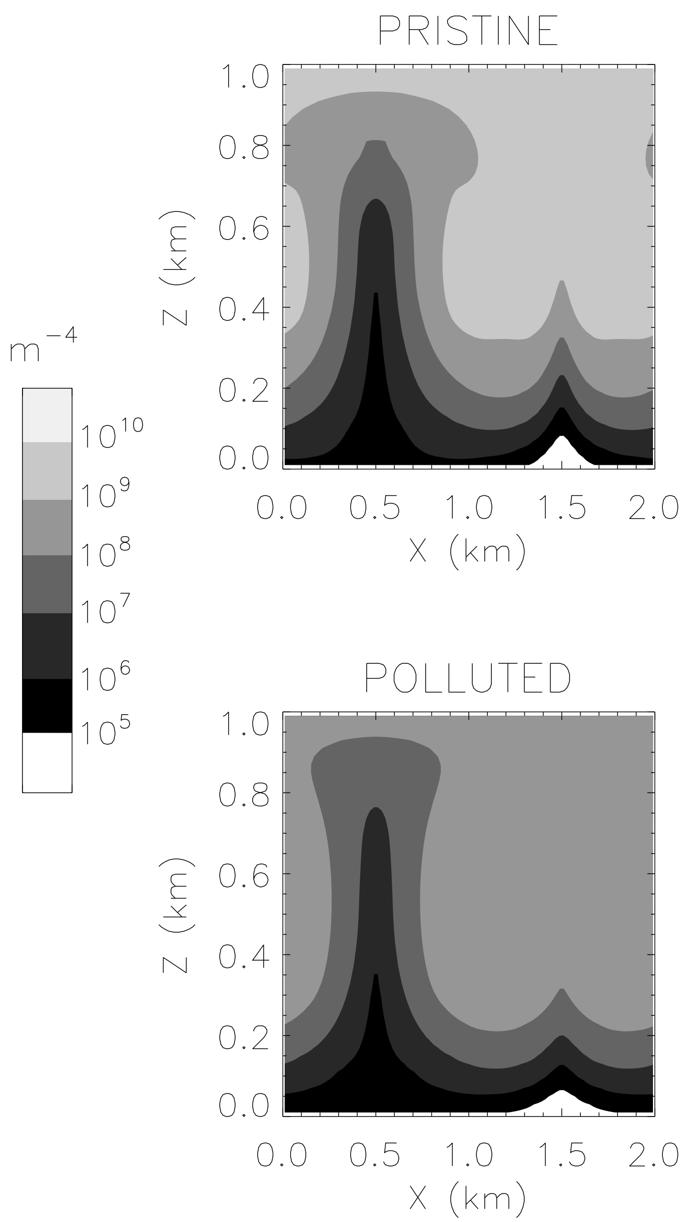

Figure 2: Equilibrium rain size distribution intercept parameter N_0 for the stratocumulus PRISTINE and POLLUTED simulations using the two-moment bulk model with KK2000.

Forcing (W m^{-2})	Scheme	Aerosol	cloud depth (m)	τ_c	CWP (g m^{-2})	N_c (cm^{-3})	$\overline{r}_e$ (μm)
3	Bin	POLLUTED	635.2	76.4	395.0	417.9	7.8
3	KK2000	POLLUTED	670.0	74.4	454.1	461.7	9.1
3	SB2001	POLLUTED	693.0	78.9	493.2	440.5	9.3
3	B1994	POLLUTED	646.6	69.8	418.9	466.7	9.0
3	$N_0 = 10^7$	POLLUTED	746.2	91.3	600.1	417.8	9.8
3	$N_0 = 10^8$	POLLUTED	675.8	74.8	467.2	423.8	9.3
3	Bin	PRISTINE	577.2	33.8	291.4	74.5	12.9
3	KK2000	PRISTINE	586.2	33.9	302.8	76.8	13.2
3	SB2001	PRISTINE	585.2	33.7	303.2	75.5	13.4
3	B1994	PRISTINE	501.2	25.6	213.4	79.3	12.4
3	$N_0 = 10^7$	PRISTINE	586.2	34.4	305.1	78.6	13.2
3	$N_0 = 10^8$	PRISTINE	638.6	39.5	378.2	70.8	14.2

Table 1: Equilibrium domain-averaged cloud depth, cloud optical depth τ_c, cloud water path (CWP), droplet number concentration (N_c), and 'effective' $\overline{r}_e$ for the stratocumulus regime. For N_c, only in-cloud regions with cloud water mixing ratio larger than 0.1 g kg^{-1} are included in the averaging. Cloud depth is calculated by defining cloud boundaries using a droplet number concentration of 1 cm^{-3}. $N_0 =$ indicates the one-moment scheme (using KK2000) with the rain intercept parameter N_0 specified at the given value. The simulations using LHF forcing of 30 W m^{-2} give a similar picture and are therefore not shown.

following Szumowski et al. (1998), the one-moment scheme is able to produce results similar to the two-moment scheme for PRISTINE (see Table 1). However, the cloud depth, CWP, and τ_c are substantially larger than produced by the two-moment scheme for POLLUTED. Increasing N_0 to 10^8 m^{-4} improves the simulation for POLLUTED, but substantially degrades CWP and τ_c for PRISTINE. These results imply that one-moment schemes with constant N_0 are inadequate when applied over a range of microphysical conditions.

a. Cumulus regime.

The cloud macrophysical and microphysical properties in the cumulus regime are strongly driven by the time-varying vertical velocity field. In all of the simulations, cloud water begins to form in the domain at t $\sim$ 6 min, followed by a rapid increase in cloud water amount as the vertical velocity increases and the eventual development of a narrow rain shaft. The domain-average CWP reaches a maximum at around the time of the maximum updraft velocity. Table 2 presents the time- and domain-averaged surface precipitation rate, CWP, N_c, τ_c, and $\overline{r}_e$ between the time of maximum updraft velocity and the end of the simulation ($t = 25$ to 60 min). As expected, N_c is much higher for POLLUTED compared to PRISTINE runs due to the higher aerosol concentration. The POLLUTED simulations all show a decrease in the overall surface precipitation rate compared to PRISTINE. The time-averaged magnitude of this suppression ranges between 0.66 and 0.93 mm hr^{-1}.

Indirect aerosol effects simulated by the different coalescence parameterizations used in the bulk model are similar, although all of the schemes, particularly KK2000, produce larger values of $\overline{r}_e$ for both POLLUTED and PRISTINE relative to the bin model. In the bulk simulations, the time-averaged difference in $\overline{r}_e$ between POLLUTED and PRISTINE (first indirect effect) is between 5.9 and 6.4 μm, while it is 6.4 μm using the bin model. The time-averaged relative increase in CWP (second indirect effect) ranges from 80% to 105% in the bulk runs. It is somewhat larger at 124% using the bin model. There is almost no difference in fractional cloud cover between the runs.

Similarly to the stratocumulus case, the intercept parameter for rain, N_0, plays a critical role in the evolution of the cloud microphysics. N_0 varies several orders of magnitude in space and time using the two moment scheme. N_0 is largest within the cloud layer, and decreases toward the surface reflecting the impact of size sorting (different mean fallspeeds are applied to N_r and q_r) and evaporation. As in the stratocumulus case, the CWP and τ_c are highly sensitive to N_0 using the one-moment scheme (see Table 2). Using a value for N_0 of 10^7 m^{-4} following Szumowski et al. (1998), this scheme produces significantly greater CWP and τ_c, and significantly less surface precipitation, relative to the two-moment scheme and the bin model. Increasing N_0 to 10^9 m^{-4} decreases the CWP and τ_c and thus improves simulation of the cloud microphysics, but the surface precipitation remains weak. The two-moment scheme, which allows N_0 to vary with the predicted N_r and q_r, produces relatively small rain drops within the cloud layer which increases residence and limits CWP, but large rain drops near the surface, which enhances the surface precipitation rate. Note that the response of the CWP and τ_c to N_0 in the one-moment scheme here is opposite in sign to that of the stratocumulus case. This difference occurs because the stratocumulus case was examined in the context of cloud characteristics that were in equilibrium with the applied forcing.

Scheme	Aerosol	PREC (mm hr^{-1})	τ_c	CWP (g m^{-2})	N_c (cm^{-3})	$\overline{r}_e$ (μm)
Bin	POLLUTED	2.17	103.4	724.5	256.7	11.1
KK2000	POLLUTED	2.50	97.6	885.5	239.6	15.7
SB2001	POLLUTED	2.70	96.1	771.5	241.6	12.7
B1994	POLLUTED	2.56	109.7	911.5	246.7	13.1
$N_0 = 10^7$	POLLUTED	0.80	165.2	1439.8	337.7	13.6
$N_0 = 10^9$	POLLUTED	0.96	103.2	830.5	265.7	12.5
Bin	PRISTINE	3.07	29.2	323.7	41.4	17.5
KK2000	PRISTINE	3.32	34.7	436.9	35.3	22.1
SB2001	PRISTINE	3.36	37.6	428.3	37.6	18.7
B1994	PRISTINE	3.49	38.2	443.9	35.9	19.0
$N_0 = 10^7$	PRISTINE	2.53	60.6	762.1	42.5	20.0
$N_0 = 10^9$	PRISTINE	1.92	43.0	493.4	41.0	18.9

Table 2: Time- and domain-averaged surface precipitation rate PREC, cloud optical depth τ_c, cloud water path (CWP), droplet number concentration (N_c), and 'effective' $\overline{r}_e$ for the cumulus regime. For N_c, only in-cloud regions with cloud water mixing ratio larger than 0.1 g kg^{-1} are included in the averaging. Time-averaging is between the time of the maximum updraft velocity and the end of the simulation (t = 25 to 60 min). $N_0 =$ indicates the one-moment scheme (using SB2001) with the rain intercept parameter N_0 specified at the given value.

3. Conclusions

The new two-moment bulk model was able to produce results generally consistent with the bin model. The decrease in $\overline{r}_e$ between PRISTINE and POLLUTED (first indirect effect) was slightly smaller (by about 1 - 1.5 μm) using the bulk models compared to the bin model for the stratocumulus regime, but quite similar for the cumulus regime. The increase in cloud water path (second indirect effect) between PRISTINE and POLLUTED using the bulk model with KK2000 and SB2001 was somewhat less than that using the bin model for the stratocumulus case. The bulk model with B1994 produced a much greater increase in cloud water path. For the cumulus case, the various bulk model simulations showed a similar increase in cloud water path between PRISTINE and POLLUTED, which was somewhat smaller than produced by the bin model. KK2000 performed best for the stratocumulus case, which is not surprising given that it was developed in the context of curve fits to bin model simulations of boundary layer stratocumulus. The SB2001 scheme also performed quite well for this case. For the cumulus case, there was generally less difference among the bulk simulations, except that KK2000 tended to produce much larger values of $\overline{r}_e$. In terms of overall performance in both regimes, SB2001 appeared to produce results that were closest to the bin model. Uncertainty in the indirect effects simulated by the bulk model may have resulted from our specification of the relative dispersion of the droplet size distribution. Sensitivity tests (not shown) indicated significant sensitivity of $\overline{r}_e$ and CWP to relative dispersion using the B1994 and SB2001 parameterizations.

A key point is that no single value of N_0 in the one-moment scheme was found that could produce results consistent with the two-moment scheme and the bin model for both the cumulus and stratocumulus regimes. The large variability in N_0 using the two-moment scheme, combined with the large sensitivity of the one-moment scheme to N_0, suggest the need to predict both q_r and N_r, and hence allow N_0 and mean rain drop size to vary as free parameters in a physically-consistent way with q_r and N_r. This may be especially important for microphysics schemes that are intended for use across a wide range of cloud types and conditions as in regional or global climate simulations using CRMs. The drawback, of course, is increased computational cost associated with the added prognostic variable. It may also be possible to diagnose N_0 for the one-moment scheme as a function of rainwater content, height, or some combination of variables that realistically captures the evolution of N_0, based on the results of the two-moment simulations.

This study was intended to gauge the ability of the bulk model to reproduce the bin model results when applied to both polluted and pristine aerosol conditions, and was not meant to quantify actual indirect effects. Thus, several simplifications were made, including neglect of cloud-aerosol feedbacks and entrainment. For application of the new microphysics scheme into CRMs with a time step of $\sim$ 10 sec and vertical grid spacing on the order of 100 m or more, the scheme will need to be modified. In particular, the approach taken here based on explicit prediction of droplet activation requires a time step less than about 1 sec and vertical grid spacing less than about 50 m. The role of mixing between a cloud and its environment and the subsequent reduction of droplet number concentration versus size also plays a key role in the microphysics of clouds and their radiative impact (Grabowski 2006). We plan to address these issues in future studies.

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