Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-64, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 16 February 2016

Atmospheric Chemistry and Physics
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The Role of the Size Distribution Shape in Determining Differences between Condensation Rates in Bin and Bulk Microphysics Schemes

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Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-64, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 16 February 2016

Abstract. The condensation rates predicted by bin and bulk microphysics schemes in the same model framework are compared in a novel way using simulations of non-precipitating shallow cumulus clouds. The bulk scheme generally predicts lower condensation rates than does the bin scheme, even when the saturation ratio and the integrated diameter of the droplet size distribution are identical. Despite other fundamental disparities between the bin and bulk condensation parameterizations, the differences in condensation rates are predominantly explained by accounting for the shape of the cloud droplet size distributions simulated by the bin scheme. This shape is not well constrained by observations and thus it is difficult to know how to appropriately specify it in double-moment bulk microphysics schemes. However, this study shows that enhancing our observations may be important since the choice of distribution shape can have a large impact on condensation rates, changing them by 50% or more in some cases.

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1. Introduction

Bin and double-moment bulk microphysics schemes are both popular approaches for parameterizing subgrid-scale cloud processes (Khain et al., 2015). In double-moment bulk schemes, the mixing ratio and total number concentration for predefined hydrometeor species are typically predicted, and a function is assumed to describe the shape of the size distribution of each species. In contrast, bin schemes do not assume a size distribution function, but instead, the distribution is broken into discrete size bins, and the mixing ratio is predicted for each bin. Usually the size of each bin is fixed, in which case the number concentration is also known for each bin.

Bin schemes, particularly those for the liquid-phase, are generally thought to describe cloud processes more realistically and accurately than bulk schemes, and thus they are often used as the benchmark simulation when comparing simulations with different microphysics schemes (e.g. Beheng, 1994; Seifert and Beheng, 2001; Morrison and Grabowski, 2007; Milbrandt and Yau, 2005; Milbrandt and McTaggart-Cowan, 2010; Kumjian et al., 2012). For the ice phase, bin schemes are plagued by many of the same issues as bulk schemes, such as the use of predefined ice habits and the conversion between ice types, rendering them not necessarily more accurate. Regardless, both liquid- and ice-phase bin schemes are much more computationally expensive since many additional variables need to be predicted. As a result, bin schemes are used less frequently. It is of interest then to see how well bulk and the more accurate liquid-phase bin microphysics schemes compare in terms of predicted process rates, and to assess how much value is added by using a bin instead of a bulk microphysics scheme.

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One of the primary drawbacks of double-moment bulk schemes that assume probability distributions is that many microphysical processes are dependent on the distribution parameters that must be either fixed or diagnosed. In the case of a gamma distribution, this parameter is typically the shape parameter. The gamma size distribution is expressed as

$$n(D) = \frac{N}{{D_n}^{\nu}\Gamma(\nu)} D^{\nu-1} e^{-D/D_n} \quad (1)$$

where ν is the shape parameter and all other symbols are defined in Table 1. Much is still to be learned regarding what the most appropriate value of this parameter is, and how it might depend on cloud microphysical properties. Figure 1 shows previously proposed relationships between the cloud droplet number concentration and the shape parameter (Grabowski, 1998; Rotstayn and Liu, 2003; Morrison and Grabowski, 2007; hereinafter G98, RL03, and MG07, respectively) along with values of the shape parameter reported in the literature and summarized by Miles et al. (2000) for several different cloud types. The figure shows a wide range of possible values of the shape parameter based on observations. The lowest reported value is 0.7 and the highest is 44.6, though this highest point is clearly an outlier. Furthermore, there is no apparent relationship with the cloud droplet concentration in the data set as a whole, and both increases and decreases of the shape parameter are found with increasing droplet concentration among individual groupings. There is also no clear dependence of the shape parameter on cloud type. Figure 1 also shows that two of the proposed functions relating these two quantities are similar (RL03 and MG07), but that the third function is in total disagreement with these first two (G98).

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Furthermore, using appropriate values of the shape parameter may be necessary for accurately modeling cloud characteristics and responses to increased aerosol concentrations. Morrison and Grabowski (2007) found that switching from the MG07 to the G98 N-v relationships in Fig. 1 led to a 25% increase in cloud water path in polluted stratocumulus clouds. This example shows that inappropriately specifying the shape parameter could have implications for the accurate simulation of not only basic cloud and radiation properties but also for the proper understanding of cloud-aerosol interactions. However, it is apparent from Fig. 1 that *large uncertainties still exist regarding the behavior of the shape parameter and how it should be represented in models*. The goal of this study is to compare the condensation and evaporation rates predicted by bin and bulk microphysics schemes in cloud-resolving simulations run using the same dynamical and modeling framework and to assess what the biggest sources of disagreement are. The focus is on condensation and evaporation since these processes occur in all clouds and are fundamental for all hydrometeor species. It will be shown that in spite of other basic differences between the particular bulk and bin microphysics schemes examined here, the lack of a prognosed shape parameter for the cloud droplet size distribution in the bulk scheme is often the primary source of differences between the two schemes, and thus an improved understanding of the shape parameter is necessary from observations and models.

2. Condensation/Evaporation Rate Formulations

The Regional Atmospheric Modeling System (RAMS) is used in this study. It contains a double-moment bulk microphysics scheme (RDB) (Saleeby et al., 2004), and the Hebrew University spectral bin model (SBM) (Khain et al., 2004). The SBM is newly implemented in RAMS. Details about the implementation can be found in Appendix A.

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In the RDB microphysics scheme, condensation/evaporation is treated with a bulk approach. Cloud droplet size distributions are assumed to conform to a gamma probability distribution given by Eq. (1). The condensation/evaporation scheme is described in detail in Walko et al. (2000), and the amount of liquid water condensed in a time step is given by their Eq. 6. Here, a slightly rearranged and simplified version of this equation is presented in order to highlight the similarities to the SBM condensation/evaporation equation shown below. Specifically, the RDB condensation/evaporation equation is written as

$$r_c^{t+\Delta t} = r_c^* + 2\pi\left[N\bar{D}\nu\left(\frac{\Gamma(\nu)}{\Gamma(\nu+3)}\right)^{1/3} f_{\nu,RBE}\right] G_{RBE}(T, r_{vs}, r_c^*)\left(S^{t+\Delta t}-1\right)\Delta t \qquad (2)$$

By using the value of S at $t+\Delta t$, the full equation for r_v (not shown) is implicit.

In contrast, the equation for the condensation/evaporation rate in the SBM is given by

$$r_c^{t+\Delta t} = r_c^* + 2\pi\left(\sum N_i D_i f_{vi,SBM}\right) G_{SBM}(T, e_s)\int_0^{\Delta t}\left(S-1\right)dt \qquad (3)$$

Semi-analytical equations are used to solve for the time integral of supersaturation that appears at the end of Eq. 3 (Khain and Sednev, 1996).

Although both equations have the same basic form, there are three primary differences in how these equations are formulated:

- In the SBM, as is required by the model structure, the condensation rate is calculated for each bin of the distribution, and these rates are then summed over all bins, as opposed to the integration of the gamma distribution that is done in the RDB scheme.

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- The formulation of the ventilation coefficients and of G_{RDB} and G_{SBM} are different, though the details will not be discussed here.
- The time step integration is performed semi-analytically in the SBM with multiple sub-time steps rather than implicitly in the RDB scheme.

These differences between the bin and bulk schemes will be taken into consideration in this analysis in order to understand why the two schemes produce different condensation rates.

3. Simulations

In order to investigate the difference in condensation rates predicted by the two microphysics schemes, simulations of *non-precipitating* shallow cumulus clouds over land were performed. This cloud type was chosen in order to minimize the indirect impacts of precipitation processes and thus facilitated the direct comparison of condensation rates. Furthermore, the daytime heating and evolution of the boundary layer results in a wider range of thermodynamic conditions than would occur in simulations of maritime clouds. The wider range of thermodynamic conditions make the conclusions of this study more robust. The simulations were run with RAMS and employed 50m horizontal spacing and 25m vertical spacing over a grid that is 12.8 x 12.8 x 3.5 km in size. The simulations are run for 9.5 hours (after this time the clouds hit the model top) using a 1s time step. The simplified profiles of potential temperature, horizontal wind speed, and water vapor mixing ratio based on an ARM SGP sounding from 6 July 1997 at 1130 UTC (630 LST) presented in Zhu and Albrecht (2003) (see their Fig. 3) are used to initialize the model horizontally homogeneously. The initial profiles of potential temperature and relative humidity are reproduced in Fig. 2. The wind direction is taken to be 0° throughout the domain. Random temperature and moisture perturbations are applied to the lowest model level at the initial time. The Harrington (1997) radiation scheme is used for simulations with both microphysics parameterizations. Surface fluxes were predicted using the LEAF-3 land surface model (Walko et al., 2000) and a short grass vegetation type was assumed.

Some modifications were made to the model for this study only in order to make the two microphysics schemes more directly comparable. The calculation of relative humidity was changed in the RDB scheme to make it the same as the calculation in the SBM. The SBM does not include a parameterization for aerosol surface deposition, so this process was turned off in the RDB scheme. Finally, the regeneration of aerosol upon droplet evaporation was deactivated in both microphysics schemes. Aerosol concentrations were initialized horizontally and vertically homogeneously. Aerosol particles did not interact with radiation.

Three simulations were run with the RDB scheme and three with the SBM scheme. Since the relationships in Fig. 1 (G98; RL03; MG07) suggest that the shape parameter may depend on the cloud droplet number concentration, the simulations were run with three different aerosol concentrations, specifically, 100, 400, and 1600 cm^{-3}, in order to obtain a larger range of droplet concentration values. The number concentration of 100 cm^{-3} is somewhat uncommon over land, but it is necessary to use this value in order to explore more fully the range of possible microphysical conditions. The simulations will be referred to by the microphysics scheme abbreviation and the initial aerosol concentration, e.g. SBM100 and RDB1600.

4. Results

4.1 Instantaneous Condensation Rates

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In order to compare directly the condensation rates predicted by the RDB and SBM microphysics schemes, it is necessary to evaluate these rates given the same thermodynamic and cloud microphysical conditions. The RDB condensation equation (Eq. (2)) is approximately proportional to four quantities: S, N, $\bar{D}$, and v. We say approximately proportional since the presence of the ventilation coefficient and the time-stepping methods make these factors not truly proportional to the condensation rate. In the SBM scheme, the condensation rate is only explicitly proportional to S, and the SBM scheme does not make assumptions about the functional form of the size distribution. If it is assumed nevertheless that the SBM size distributions can be described by some probability distribution function (which doesn't necessarily have to be a gamma distribution), then Eq. (3) could also be rewritten to be approximately proportional to N and $\bar{D}$. Therefore, in order to compare best the condensation rates between the two schemes, the condensation and evaporation rates that occur during one time step were binned by the values of S and $N\bar{D}$ (hereafter referred to as the integrated diameter) that existed at the start of the condensation/evaporation process and were averaged in each bin. Where the cloud was supersaturated and subsaturated, saturation ratio bin widths of 0.1 and 1 were used, respectively. For $N\bar{D}$, bin widths of 0.05 m g^{-1} were used. The output from the model only includes the values of S, N, and $\bar{D}$ after condensation and evaporation have occurred. However, since the rates of condensation and droplet nucleation were known, and since microphysics is the last physical process to occur during a time step in RAMS, the S, N and $\bar{D}$ that existed before condensation occurred were easily obtained. All points where the cloud mixing ratio before condensation was greater than 0.01 g kg^{-1} are included in the analysis.

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Note that the aerosol activation parameterizations in the RDB and SBM microphysics are not the same, and hence the number of nucleated cloud droplets is not the same. This will impact the frequency at which each joint S and $N\bar{D}$ bin occurs. However, we are primarily concerned with the average condensation rate in each joint bin, and the average value will not be impacted by the aerosol activation parameterizations since we are explicitly accounting for differences in the number and size of droplets through the use of $N\bar{D}$ in our analysis. Therefore the differences in the aerosol activation parameterizations should not influence the differences in the average condensation rates as evaluated in our framework.

The average condensation rate in each S and $N\bar{D}$ bin was calculated for all simulations. Figure 3 shows an example of this calculation for one simulation. As is seen in Fig. 3, there is a smooth transition to higher condensation rates as the saturation ratio increaeses, and to higher condensation ($S \geq 1$) and evaporation ($S<1$) rates as the integrated diameter increases. This is expected based on the condensation equations (Eqs. (2), (3)). All other simulations behave similarly.

In order to compare easily the condensation rates predicted by the two microphysics schemes, Fig. 4a-c shows the ratio of the RDB to SBM condensation rates in the S and $N\bar{D}$ phase space. It reveals that for low integrated diameter values, the RDB scheme predicts higher condensation rates, but that almost everywhere else, the condensation rate is higher in the SBM scheme simulations. In the RDB1600 and SBM1600 simulations, the RDB scheme predicts lower condensation rates almost everywhere. In all cases, the ratios are lowest (RDB rates are lower than SBM rates) where $N\bar{D}$ is large.

For evaporation (Fig. 3d-f), the RDB and SBM rates are more similar than for condensation. The disagreement is worst for very low relative humidity values, very low integrated diameter values, as well as for moderate values of both quantities. In all of these cases, the difference is 25% or more. However, where evaporation occurs most frequently (at high saturation ratio and low integrated diameter; not shown), the differences are generally less than 10%. Thus it appears that the evaporation rates between the two schemes generally agree better than do the condensation rates.

There are many potential reasons why the condensation and evaporation rates are different between the two schemes. As the following analysis will show, one major source of discrepancy is that the cloud droplet size distribution assumed by the RDB scheme is not always representative of what the SBM scheme simulates.

4.2 Shape Parameter

As can be seen in the condensation equation for the RDB scheme (Eq. 2), when a gamma distribution is assumed, the condensation rate is proportional to the shape parameter ν such that a higher shape parameter results in higher condensation rates. The SBM scheme makes no assumptions about the size distribution shape. However, in order to characterize the predicted SBM size distributions, and to facilitate the comparison of the SBM and RDB condensation rates, we assume that the predicted SBM size distributions are gamma distribution-like and find the best-fit gamma distribution parameters (see Eq. (1)) for the cloud droplet size distributions at every cloudy grid point in the SBM simulations. We then evaluate the mean best-fit shape

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parameter for each point in the S and $N\overline{D}$ phase space. These best-fit shape parameters are then used to assess whether the assumption of a constant shape parameter could explain differences between the RDB and SBM average condensation rates

In order to find the best-fit shape parameters, we define cloud droplets as belonging to one of the first 15 bins of the SBM liquid array, which corresponds to a maximum cloud droplet diameter of 50.8 μm. Many methods are available to find such best-fit parameters, but they generally all give similar results (McFarquhar et al., 2014). Here we use the maximum-likelihood estimation method and find best-fits that minimize the error in the total number concentration. Using this method, the size distributions are first normalized by the corresponding total number concentration, leaving only D_n and v as free parameters of the distribution (Eq. 1).

Note that while we could determine the values of S and $N\overline{D}$ that existed before condensation occurred, we cannot determine the value of the best-fit shape parameter for this time because the change in mixing ratio of each bin is not output by RAMS. Thus the average shape parameters used in the analysis are those that exist at the end of the time step. Nonetheless, given the short time step used in these simulations, it is not expected that the best-fit shape parameter would change much in one time step and thus the impact of using the post-condensation shape parameters is not expected to have a large impact on the results.

Figure 5 displays a scatterplot of the average shape parameters and the condensation and evaporation rate ratios presented in Fig. 4 for each of the three sets of simulations. The black line plotted in all three panels is the same and shows the theoretical condensation rate ratio that we

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would expect if there were no other differences between the bin and bulk condensation equations aside from the value of the shape parameter (and assuming that the bin scheme always predicts cloud droplet size distributions that conform to a gamma distribution). Recall that in the RDB simulations the shape parameter is constant and has a value of 4. Therefore, specifically, the line is equal to $4\left(\frac{\Gamma(4)}{\Gamma(7)}\right)^{1/3} \Big/ \nu\left(\frac{\Gamma(\nu)}{\Gamma(\nu+3)}\right)^{1/3}$ (see the ν dependency in Eq. 2).

In all three pairs of simulations, the mean shape parameter in the SBM simulations explains a large fraction of the variability in the condensation rate ratios, particularly for points with a supersaturation greater than 0.1% (blue dots) or a relative humidity between 90 and 99% (yellow dots). Note that at low shape parameter values, both the theoretical ratio and the modeled ratios indicate that the RDB prediction can be 50% higher than the SBM prediction or more. As the initial aerosol concentration increases, the spread of the points in these two categories around the theoretical expectation increases but is otherwise qualitatively similar. The increased spread is in part due to the fact that the RDB1600 and SBM1600 simulations cover a larger area of the S and $N\bar{D}$ phase space (Fig. 4). Therefore there are more points displayed in Fig. 5c and each point has on average fewer instances of condensation included in its average (not shown). As a result, it is difficult to draw conclusions about how the bulk versus bin condensation rates change as a function of the initial aerosol concentration, except to say that aside from the change in spread, there are no startling differences.

The quality of the match between the predicted and the model-derived condensation ratios is lower for points with relative humidity values close to saturation (99-100.1%; orange dots).

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These points tend to lie much farther from the predicted ratio line and show less correlation with the mean shape parameter value. Many points in this category instead have ratios near 1, indicating that both schemes predict the same condensation/evaporation rates. For these points, it is likely that the supersaturation or subsaturation is entirely removed in one time step. In such a case, the shape of the droplet size distribution, as well as all of the other scheme differences, has no impact on the condensation/evaporation rate. If, on the other hand, the supersaturation or subsaturation is nearly, but not entirely removed, the predicted rate is likely sensitive to the scheme's time stepping method and large differences between the condensation/evaporation rates predicted by the two schemes can arise. Finally, at high sub-saturation (0-89% RH; purple dots), the ability of the shape parameter to predict the condensation rate ratio is also diminished. In this regime, cloud water mixing ratio is low and droplets are small. Any of the other differences between the two condensation schemes could be responsible for the disagreement here.

5. Discussion and Conclusions

In this study we have conducted a comparison of the condensation rates predicted by a bulk and a bin microphysics scheme in simulations of non-precipitating cumulus clouds run using the same dynamical framework, namely RAMS. The simulations were run with three different background aerosol concentrations in order to consider a large range of microphysical conditions. When the condensation rates were binned by saturation ratio and integrated diameter, the RDB rates were on average higher only for evaporation at low relative humidities and for condensation at low integrated diameter values. Otherwise, the RDB condensation and evaporation rates were consistently lower than those predicted by the SBM. Further analysis indicated that the fixed shape parameter assumed for RDB cloud droplet size distributions

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explained much of the discrepancy in condensation rates between the two schemes, particularly when the supersaturation was greater than 0.1% or the relative humidity was 90-99%. For relative humidity values close to 100% (99-100.1%), the two schemes often predicted similar rates regardless of the best-fit shape parameter values from the SBM. A number of conclusions can be drawn from these results:

1. A gamma probability distribution appears to be a good assumption for the cloud droplet distribution shape, and the exact knowledge of the distribution shape in a bin scheme is often not necessary to minimize errors in the condensation rate in bulk schemes.
2. Given that the shape parameter associated with the bin scheme cloud distributions explains the condensation rate ratios well under most conditions, differences in the formulations of the ventilation coefficient and G terms may not be important except possibly when the relative humidity is low.
3. For relative humidity conditions near saturation, the rates predicted by bin and bulk schemes are often similar since the supersaturation or subsaturation is entirely consumed in one time step. If, on the other hand, the supersaturation or subsaturation is only mostly removed, then large discrepancies in the condensation rates may appear.
4. Except when small residual supersaturation or subsaturation remains at the end of the model time step, the multiple sub-time steps taken by the SBM scheme may not strongly impact the total amount of condensed water in the full time-step and thus it may not be necessary to use such computationally expensive methods.

In conclusion, it appears that *the most important factor for agreement in cloud droplet condensation rates between bin and bulk schemes is the shape of the cloud droplet size*

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distribution. And while we have not explicitly explored them here, we would expect this basic conclusion to hold for other hydrometeor types as well.

We have presented here a novel method for comparing condensation rates between any two microphysics schemes. Although we have only investigated two specific schemes, it is expected that the results can be applied more generally to bulk and bin schemes. Additional work should be conducted using a similar approach in order to compare and evaluate additional microphysics schemes and additional microphysical processes. While it is clear that the effective shape parameter in the bin simulations explains much of the discrepancies in predicted condensation rates between bin and bulk schemes, and that the shape parameter value can change the condensation rate by 50% or more, our understanding of what the most appropriate value of the shape parameter is or how it should vary as a function of basic cloud properties is limited. More work then is also needed on understanding cloud droplet distributions from observations and measurements.

Acknowledgements:
The authors thank Alexander Khain for generously sharing his SBM code in order to make this study possible. This material is based on work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1321845 and the National Aeronautics and Space Administration Grant No. NNX13AQ32G. Additional information can be found in the supporting information or be requested from the corresponding author.

Appendix A

Implementation of the Hebrew University SBM scheme into RAMS

While the present study is only concerned with warm phase processes, the methods to interface the Hebrew University SBM scheme with the RAMS radiation scheme (Harrington, 1997) will be described here, including those for the ice species. The RAMS radiation scheme uses pre-computed lookup tables for the extinction coefficient, single-scattering albedo, and asymmetry parameter for each hydrometeor species. Three of the hydrometeor species in the SBM correspond directly to species in the RAMS microphysics scheme, namely, aggregates, graupel, and hail. All liquid drops are represented as one species in the SBM, so these liquid bins are classified as either cloud droplets or rain drops using the same size threshold used by the RAMS microphysics scheme to distinguish these two species. Finally, the SBM represents three ice crystal types – plates, columns, and dendrites. Separate RAMS radiation look-up tables already exist for these different ice crystal types, but like for cloud and rain, there are two tables for each crystal type depending on the mean size of the crystals. In RAMS, the small ice crystals are referred to as pristine ice, and the large ice crystals as snow. Again, the same size threshold used to distinguish these two ice categories is used to assign bins from the SBM ice crystal species as either pristine ice or snow. This fortuitous overlap in the ice species has allowed for the seamless integration of the SBM hydrometeor species with the RAMS radiation scheme. For each set of SBM bins that corresponds to a RAMS species, the total number concentration and mean diameter is calculated, a gamma distribution shape parameter of 2 is assumed, and the appropriate set of look-up tables for the corresponding RAMS species is used for all radiative calculations.

References:

Beheng, K. D.: A parameterization of warm cloud microphysical conversion processes, Atmos. Res., 33, 193–206, doi:10.1016/0169-8095(94)90020-5, 1994.

Grabowski, W. W.: Toward Cloud Resolving Modeling of Large-Scale Tropical Circulations: A Simple Cloud Microphysics Parameterization, J. Atmos. Sci., 55(21), 3283–3298, doi:10.1175/1520-0469(1998)055<3283:TCRMOL>2.0.CO;2, 1998.

Harrington, J. Y.: The effects of radiative and microphysical processes on simulation of warm and transition season Arctic stratus, Colorado State University., 1997.

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A. and Phillips, V.: Simulation of Effects of Atmospheric Aerosols on Deep Turbulent Convective Clouds Using a Spectral Microphysics Mixed-Phase Cumulus Cloud Model. Part I: Model Description and Possible Applications, J. Atmos. Sci., 61(24), 2963–2982, doi:10.1175/JAS-3350.1, 2004.

Khain, A. P. and Sednev, I.: Simulation of precipitation formation in the Eastern Mediterranean coastal zone using a spectral microphysics cloud ensemble model, Atmos. Res., 43(1), 77–110, doi:10.1016/S0169-8095(96)00005-1, 1996.

Khain, A. P., Beheng, K. D., Heymsfield, A., Korolev, A., Krichak, S. O., Levin, Z., Pinsky, M., Phillips, V., Prabhakaran, T., Teller, A., van den Heever, S. C. and Yano, J.-I.: Representation of microphysical processes in cloud-resolving models: Spectral (bin) microphysics versus

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Manuscript under review for journal Atmos. Chem. Phys.
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bulk parameterization, Rev. Geophys., 53(2), 247–322, doi:10.1002/2014RG000468, 2015.

Kumjian, M. R., Ganson, S. M. and Ryzhkov, A. V.: Freezing of Raindrops in Deep Convective Updrafts: A Microphysical and Polarimetric Model, J. Atmos. Sci., 69(12), 3471–3490, doi:10.1175/JAS-D-12-067.1, 2012.

McFarquhar, G. M., Hsieh, T.-L., Freer, M., Mascio, J. and Jewett, B. F.: The Characterization of Ice Hydrometeor Gamma Size Distributions as Volumes in $N_0 - \lambda - \mu$ Phase Space: Implications for Microphysical Process Modeling, J. Atmos. Sci., 72(2), 892–909, doi:10.1175/JAS-D-14-0011.1, 2015.

Milbrandt, J. A. and McTaggart-Cowan, R.: Sedimentation-Induced Errors in Bulk Microphysics Schemes, J. Atmos. Sci., 67(12), 3931–3948, doi:10.1175/2010JAS3541.1, 2010.

Milbrandt, J. A. and Yau, M. K.: A Multimoment Bulk Microphysics Parameterization. Part I: Analysis of the Role of the Spectral Shape Parameter, J. Atmos. Sci., 62(9), 3051–3064, doi:10.1175/JAS3534.1, 2005.

Miles, N. L., Verlinde, J. and Clothiaux, E. E.: Cloud Droplet Size Distributions in Low-Level Stratiform Clouds, J. Atmos. Sci., 57(2), 295–311, doi:10.1175/1520-0469(2000)057<0295:CDSDIL>2.0.CO;2, 2000.

Morrison, H. and Grabowski, W. W.: Comparison of Bulk and Bin Warm-Rain Microphysics Models Using a Kinematic Framework, J. Atmos. Sci., 64(8), 2839–2861, doi:10.1175/JAS3980, 2007.

Rotstayn, L. D. and Liu, Y.: Sensitivity of the First Indirect Aerosol Effect to an Increase of Cloud Droplet Spectral Dispersion with Droplet Number Concentration, J. Clim., 16(21), 3476–3481, doi:10.1175/1520-0442(2003)016<3476:SOTFIA>2.0.CO;2, 2003.

Saleeby, S. M. and Cotton, W. R.: A Large-Droplet Mode and Prognostic Number Concentration of Cloud Droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS). Part I: Module Descriptions and Supercell Test Simulations, J. Appl. Meteorol., 43(1), 182–195, doi:10.1175/1520-0450(2004)043<0182:ALMAPN>2.0.CO;2, 2004.

Saleeby, S. M. and van den Heever, S. C.: Developments in the CSU-RAMS Aerosol Model: Emissions, Nucleation, Regeneration, Deposition, and Radiation, J. Appl. Meteorol. Climatol., 52(12), 2601–2622, doi:10.1175/JAMC-D-12-0312.1, 2013.

Seifert, A. and Beheng, K. D.: A double-moment parameterization for simulating autoconversion, accretion and selfcollection, Atmos. Res., 59-60, 265–281, doi:10.1016/S0169-8095(01)00126-0, 2001.

Walko, R. L., Band, L. E., Baron, J., Kittel, T. G. F., Lammers, R., Lee, T. J., Ojima, D., Pielke, R.

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Published: 16 February 2016

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A., Taylor, C., Tague, C., Tremback, C. J. and Vidale, P. L.: Coupled atmosphere, biophysics and hydrology models for environmental modeling, J. Appl. Meteorol., 39, 931–944, doi:10.1175/1520-0450(2000)039<0931:CABHMF>2.0.CO;2, 2000a.

Walko, R. L., Cotton, W. R., Feingold, G. and Stevens, B.: Efficient computation of vapor and heat diffusion between hydrometeors in a numerical model, Atmos. Res., 53(1-3), 171–183, doi:10.1016/S0169-8095(99)00044-7, 2000b.

Zhu, P. and Albrecht, B.: Large eddy simulations of continental shallow cumulus convection, J. Geophys. Res., 108(D15), 4453, doi:10.1029/2002JD003119, 2003.

Table 1. Definitions of symbols used.

Symbol	Definition
e_s	Saturation water vapor pressure
D	Cloud droplet diameter
$\bar{D}$	Volume mean cloud droplet diameter. $r_c=\pi\rho_w N\bar{D}^3/6$
D_n	Characteristic cloud droplet diameter. $D_n^3=\bar{D}^3\Gamma(v)/\Gamma(v+3)$
$f_{v,RDB}$, $f_{v,SBM}$	Ventilation coefficients for the RDB and SBM schemes, respectively
G_{RDB}, G_{SBM}	Term to account of the impact of latent heat release on the condensation process. See *Walko et al.* [2000] and *Khain and Sednev* [1996] for the formulations used in the RDB and SBM schemes, respectively
N	Cloud droplet number concentration
n	Concentration of cloud droplets per unit cloud droplet diameter interval
r_c	Cloud water mixing ratio
r_v	Water vapor mixing ratio
r_{vs}	Saturated water vapor mixing ratio
S	Saturation ratio
T	Air temperature
t	Time
Γ	Gamma function
v	Gamma distribution shape parameter
$(\ )^*$	Value of a quantity after advection and all other model processes but before microphysical processes have occurred during a model time step

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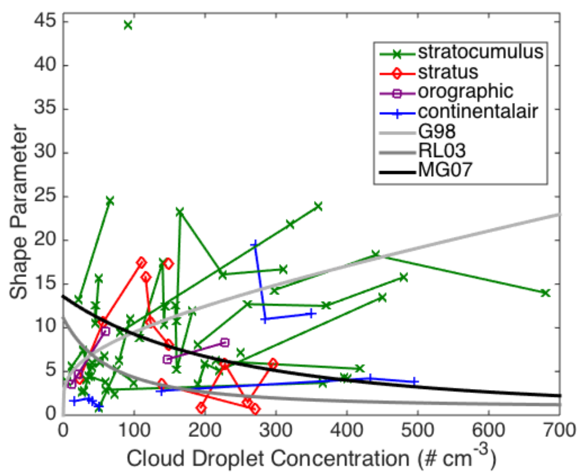

Figure 1. Shape parameter (ν) values as a function of cloud droplet concentration as reported by Miles et al. (2000) using 16 previous studies. Values, cloud classification, and groupings are based on their Tables 1 and 2. The three solid gray lines show proposed relationships between the cloud droplet concentration and the shape parameter. G98 is from Eq. 9 in Grabowski (1998). RL03 is from Eq. 3 in Rotstayn and Liu (2003) with their α=0.003. MG07 is from Eq. 2 in Morrison and Grabowski (2007). All equations were originally written for relative dispersion, which is equal to $\nu^{-1/2}$, and have been converted to equations for ν for this figure.

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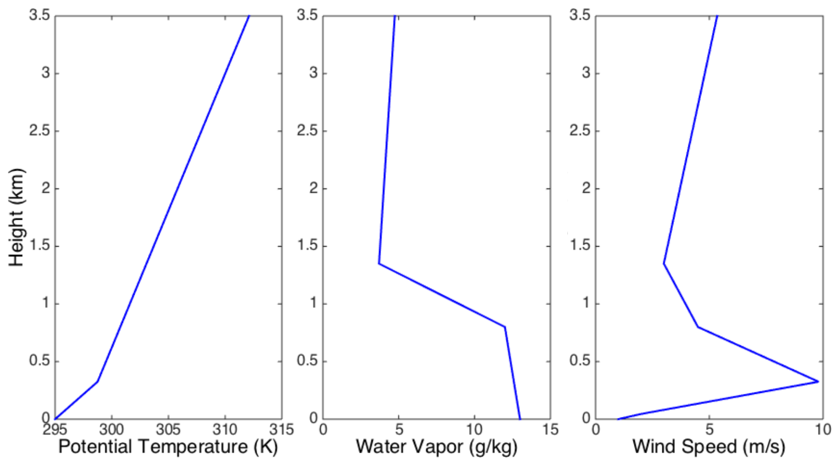

Figure 2. Profiles of potential temperature, water vapor, and wind speed used to initialize the simulations from Zhu and Albrecht (2003).

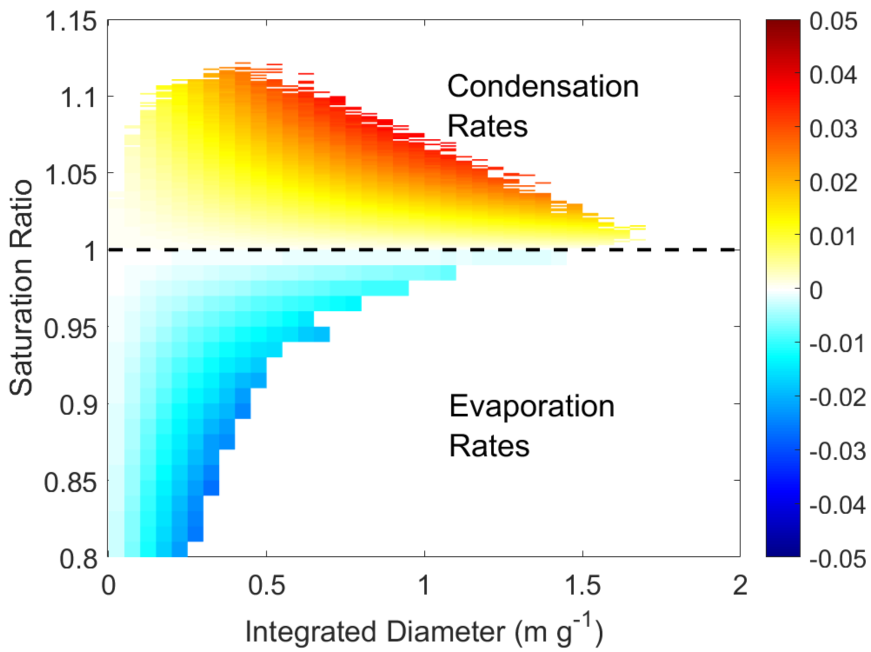

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Figure 3. The average condensation and evaporation rates (g kg^{-1} s^{-1}) as a function of saturation ratio (S) and integrated diameter ($N\bar{D}$) for the SBM100 simulation.

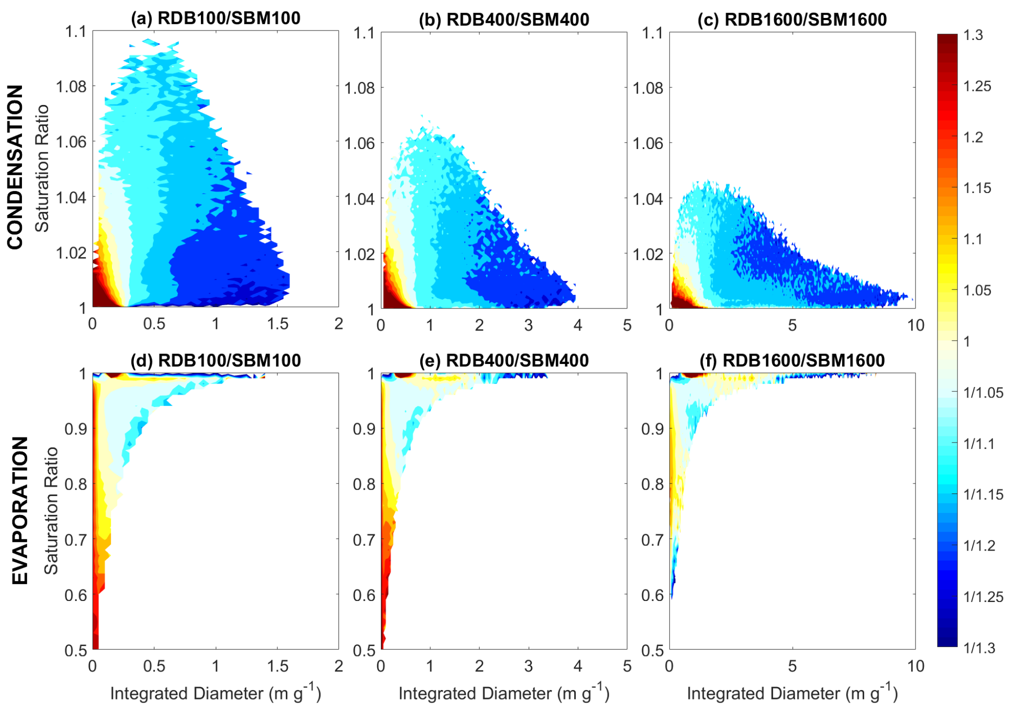

Figure 4. The ratio of the RDB to SBM (a-c) condensation and (d-f) evaporation rates as a function of saturation ratio (S) and integrated diameter ($N\bar{D}$) for each pair of simulations. Note the differences in axes limits.

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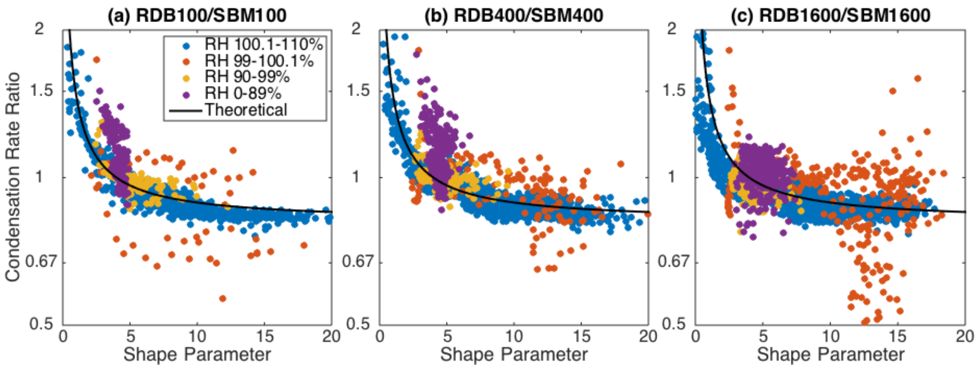

Figure 5. Scatterplots of the condensation rate ratios (RDB/SBM) and mean best-fit shape parameters from the SBM simulations. Each point shows values from a joint bin in the S and $N\bar{D}$ phase space in Figure 3. The black line is identical in all three plots and displays the theoretical condensation rate ratio obtained by assuming that no other differences exist between the two schemes aside from the value of the best-fit shape parameter. See the text for more details.