We would like to thank all three referees for taking the time to review our manuscript. All referees felt that the manuscript was confusing, and we have substantially revised the manuscript to address these concerns, including a modified methodology, new figures, and clearer discussion. The basic conclusions have not changed, but we feel that they are now better explained and better substantiated. Responses to specific comments are below.

Anonymous Referee #1

Received and published: 11 March 2016

Review of “The role of the size distribution shape in determining differences between condensation rates in bin and bulk microphysical schemes” by Igel and van den Heever. This is a confusing manuscript of very little significance for modeling of atmospheric clouds in my opinion. I have several general and many specific comments that need to be addressed before the manuscript is accepted in ACP. Because of little significance, I do not want to re-review the revised manuscript. The handling Editor should be able to judge if my comments are appropriately addressed.

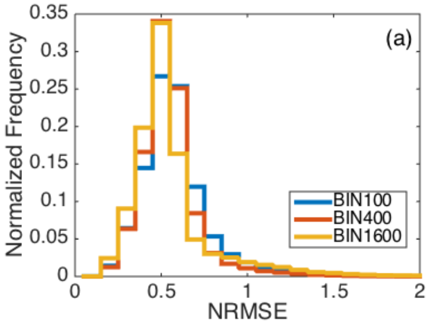
We have addressed the general and specific comments below. Here we would like to address the comment regarding significance. Bin and bulk microphysics schemes take fundamentally different approaches to describing cloud size distributions. Because bin schemes are much more expensive computationally, but otherwise generally believed to be superior, there is a need to understand how bulk schemes can be improved based on the behavior of bin schemes. We believe that this paper makes a significant contribution towards identifying the important and unimportant differences between the two schemes. Specifically, our results suggest that an assumed gamma size distribution by bulk schemes does NOT induce a large degree of error *if the correct value of the shape parameter can be known*. We feel that this is a significant conclusion, and one that is not obvious or expected. Given the multiple questions raised by the referee about the inappropriateness of the gamma distribution and multimodality, they do not seem to think that this is an obvious or expected result either.

General comments.

1. I found the whole logic behind this paper (including the title) confusing. Unless cloud droplets are very small (in which case surface tension, solute, and molecular effects need to be considered) or they are large (tens of microns, in which case ventilation effects are important), the condensation rate for a given supersaturation depends on the integral radius alone, that is, on the integral of the product of the droplet concentration and the droplet radius. (This is incorrectly called “integrated radius” in the manuscript). The reference to the spectral shape is confusing because the condensation rate depends on the spectral shape indirectly. For instance, if the spectrum is symmetric, the spectral width is irrelevant because in such case the integral radius is independent of the width. Of course the gamma distribution is asymmetric. The difference between the condensation rate as given by Eqs. (2) and (3) is that the assumed droplet distribution is analytically integrated in (2) in contrast to the approximation of the integral by the sum over finite number of bins in (3). So the difference may come from the assumed shape of the spectrum in the bulk scheme (in contrast to freely-evolving shape in the bin scheme), but it may also come from an inaccurate representation of the spectrum with a small number of bins (note that the number of bins is rather low in the Khain’s scheme).

We agree with the reviewer that the impact of the spectral width will depend on the asymmetry of the size distribution, and will have no impact in the case of a symmetric distribution. What we find powerful is that when we assume a specific distribution function – specifically, the gamma distribution function, which as noted by the reviewer is asymmetric – the shape parameter (which quantifies the spectral width) *IS* able to account for much of the discrepancies in the condensation/evaporation rate between the two schemes, despite all of the potential pitfalls that the reviewer mentions such as the potential inaccurate representation of the droplet spectrum, or the potential for multi-modal or non-gamma-like distributions. We too would have expected such issues to be more important and thus we think that the conclusions we draw are important and worthy of publication.

2. The gamma size distribution is perhaps a sensible representation of possible droplet spectral shapes, but it is by no means ideal. Realistic situations involve various shapes, including often-observed bimodal spectra and occasional multi-modal. Such spectra cannot be represented by the gamma distribution, but can be simulated by the bin scheme. So how important are the spectral shape differences simulated in the current study? Are the differences in the condensation rate correlated with the asymmetry and/or multimodality of the spectra simulated by the bin scheme? We agree that the gamma size distribution is by no means ideal. We calculated the normalized root mean square error for each of the fitted gamma distributions from the bin simulations. A value of 1 indicates that the fit is better than a straight line. The NRMSE's are generally less than 1 and indicate that most of the time the gamma distribution has some skill in approximating the simulated size distribution. (We recognize that this doesn't necessarily mean that a different distribution wouldn't be better.) We have also attempted to assess how these cloud droplet size distributions with poor fits impact the comparison with the bulk scheme condensation and evaporation rates. There is an entirely new section of the manuscript dedicated to this topic. In summary, we do not find that the non-gamma-like DSDs severely deteriorate the comparison of the rates. This is both because they do not occur very frequently, and because even with only a mediocre fit, the best-fit shape parameters still seem to be able to account for much of the difference between the bulk and bin scheme condensation and evaporation rates. It is certainly not perfect, but it is an improvement.



Above: Distribution of NRMSE values from the three bin simulations.

3. I think differences shown in the paper need to be put in the context of bulk cloud properties to see if they play any role. The fact that condensation rates differ for given supersaturation and integral radius tells me little because of the interactive nature of the condensation. In a real situation, a different condensation rate modifies the super-saturation and the overall effect might

be insignificant. In other words, one needs to see the change of the supersaturation for a modified condensation rate, and not the condensation rate for a given supersaturation. Think quasi-equilibrium supersaturation. Does the simulation applying one formulation differ significantly from the other? If not, then why worry?

The short answer is that yes, changing the value of the shape parameter in a bulk simulation can have large impacts on the cloud properties. These changes are discussed in detail in Igel et al. 2016b (accepted pending revision). We know more generally that bin and bulk schemes (or more generally any two microphysics schemes) often simulate very different cloud properties and we have very little understanding about why this is the case. Even if differences in the condensation and evaporation formulations do not turn out to cause the simulations to be different from one another, this would be worth knowing since we do not know which microphysical processes contribute most to the differences. This study is just one step towards understanding the behavior of these different schemes.

In regards to quasi-equilibrium supersaturation, we see the referee's point that it may not matter how we get to equilibrium if the equilibrium state itself is the same regardless of the scheme. We also agree that analyzing the change in supersaturation in a similar way as we have done for the condensation and evaporation rates could be interesting, but we are not sure what additional information that would give. We have found that the mean supersaturation can vary by 0.2-0.4% depending on the shape parameter used in the bulk simulations which suggests that the quasi-equilibrium state is not the same. Furthermore, the concept of quasi-equilibrium only applies to the cloud core. By our estimate, at most 25% of the cloudy points are in the cloud core (this is the percent of cloudy points that are both supersaturated and in an updraft). Given that 75% of cloudy points not in the cloud core, and that the quasi-equilibrium is impacted, we think that the understanding how the condensation and evaporation rates differ between the schemes is important.

Specific comments

1. Abstract. L. 14: I do not consider the approach used in the paper particularly novel.

It is not an approach we have seen others use to compare microphysics schemes.

L. 16: "Integrated diameter" should be "integral diameter" (and in many paces in the text).

We have revised the analysis such that this term is no longer used at all.

L. 23: The fact that the maximum deviation may reach 50% tells me little. What about the mean or median inside each bin? And what impact does it have on cloud properties? See 3 above.

In the revised manuscript, we discuss in detail the means of the bins. The impact of a change in the shape parameter on cloud properties is discussed in Igel et al. 2016b (accepted pending revision).

2. L. 71/72: Was the change in Morrison and Grabowski related to condensation or to the drizzle formation? I think the latter. If so, this is really not relevant to the subject matter of this paper.

Morrison and Grabowski do not discuss the reasons for why a change in the N-ν relationships changed the cloud water path.

3. Section 2, modeling setup. I am curious why such a complex modeling setup was chosen, with

interactive land-surface model and radiation. There exist much simpler cases (like BOMEX or RICO for the maritime environment or diurnal cycle of shallow convection over the ARM SGP by Brown et al. QJ). A simpler case eliminates feedbacks between clouds and other processes that can make the simulations with different microphysics schemes to diverge more rapidly. The two simulations diverge eventually (the butterfly effect), correct? Moreover, if such a simpler and already documented case is used, the simulation can be compared with results from other models and give more credibility to RAMS results.
These simulations were used for additional studies (Igel et al. 2016a, b, accepted pending revision). The details are provided for completeness, although we agree that a simpler set-up could have been used.

4. Walko et al (2000) is actually two papers, 2000a and 2000b. However, (2) is not presented in Walko et al. so a different reference is needed. Moreover, Walko et al. paper starts with the invariant temperature proposed by Tripoli and Cotton. How is this relevant for a scheme that predicts the supersaturation? Something is not correct here. Also, RAMS use to have a much better bin microphysics (when Stevens and Feingold were at CSU), without ice, but with a significantly better representation of warm-rain processes (double-moment). One can enhance this study using that bin scheme in the comparison as well (just a comment).
Yes, there are two Walko et al (2000) studies and we neglected to indicate which we were referring to. It is 2000b. We are aware that Eq. 2 is not in Walko et al. (2000b), which is why we have explicitly stated that Eq. 2 is a rearranged and simplified version of Walko's Eq. 6. There exists no reference for Eq. 2.

We assume that the reviewer is asking about the use of the ice-liquid temperature. This temperature is invariant for internal water phase changes and does not rely on any assumptions about saturation. Thus, it is perfectly suitable for use in a condensation schemes that allows for supersaturation.

The former bin scheme in RAMS is not available in the standard code and thus was not available for comparison.

5. L. 111/112. This is not correct. Condensation in the bin scheme results in the shift of droplets from one bin to the next one.
True, the end result is that droplets shift bins. However, this shifting is only done after the calculation of condensation rates. The shifting of droplets is done in such a way as to conserve the new total mass, total number, and total reflectivity of the droplet population.

6. L. 129/130. If clouds reach the model top, the domain is too shallow, even a few hours earlier. This is bad experimental design.
At the final time included in our analysis, the maximum cloud top is about 750m from the model top. This may indeed be too close, but based on examination of the vertical velocity vertical profiles, we believe that the clouds may be too close to the top for at most only the last hour. However, since we are not examining cloud macrophysical properties or evolution, but rather only instantaneous condensation and evaporation rates, the location of the clouds relative to the model top is not at all an issue for our analysis.

7. L. 143, “aerosol surface deposition”. What is that? Please explain.

We mean dry deposition or gravitational settling. This has been clarified within the manuscript.

8. L. 148/155. How many bin are used in the bin code? Are results sensitive to the number of bins used? What is the shape parameter value for the bulk scheme?

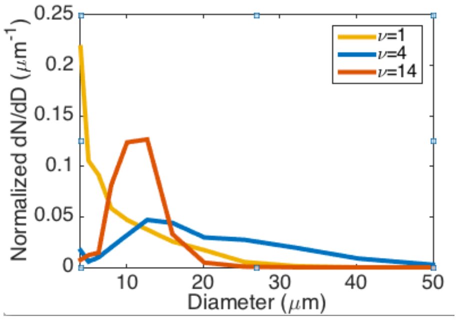
The SBM uses 33 mass-doubling bins. We cannot easily test the sensitivity of the results to the number of bins used without significantly restructuring the code. The shape parameter for the bulk scheme was originally 4. We now also test values of 2 and 7.

9. L. 173 and several other places. What is “saturation ratio”? Please define.

It is now defined. It is the same as relative humidity except not multiplied by 100%.

10. Section 4.2. It is unclear to me why one might expect that a bin scheme with a small number of bins can provide a useful estimate of the shape parameter. This is clearly impossible for bimodal and multimodal spectra. At least a comment on this would be appropriate.

We believe that 33 bins are more than sufficient to capture bimodal distributions and to find a shape parameter for each mode. The following figure shows three example distributions simulated by the bin scheme. This figure shows only the first 15 bins, and the legend indicates the best-fit shape parameter. The scheme can clearly produce droplet size distributions that have distinct widths and that can be well-characterized by a shape parameter. Similarly variations in behavior can be captured with the remaining 18 bins, which are for raindrop-sized drops. Thus with 33 total bins, the bimodal nature of the cloud-rain size distribution is can be simulated.



11. L. 316 and abstract: It is obviously the shape of the spectrum (prescribed in the bin scheme and evolving freely in the bin scheme) that is responsible for the difference between the two schemes. So this conclusion is kind of obvious. Please see my general comment 1.

See also our response to comment 1.

12. The appendix provides very little useful information and can be removed from the manuscript.

We agree that the appendix is not particularly relevant to the study, however we choose to keep it to document the implementation of the SBM into RAMS.

References:

Igel, A.L. and S.C. van den Heever, 2016a: The importance of the shape of cloud droplet size distributions in shallow cumulus clouds. Part I: Bin microphysics simulations. Accepted pending revision at *J. Atmos. Sci.*

Igel, A.L. and S.C. van den Heever, 2016b: The importance of the shape of cloud droplet size distributions in shallow cumulus clouds. Part II: Bulk microphysics simulations. Accepted pending revision at *J. Atmos. Sci.*

We would like to thank all three referees for taking the time to review our manuscript. All referees felt that the manuscript was confusing, and we have substantially revised the manuscript to address these concerns, including a modified methodology, new figures, and clearer discussion. The basic conclusions have not changed, but we feel that they are now better explained and better substantiated. Responses to specific comments are below.

Anonymous Referee #2

Received and published: 25 March 2016

Review of “The role of the size distribution shape in determining differences between condensation rates in bin and bulk microphysics schemes”

In this manuscript the authors argue that the shape parameter of bulk distributions is important in models to properly understand cloud properties as well and process rates.
The problem is that the shape parameter is highly variable. They argue that the shape parameter accounts for much of the difference in condensation rates between bin an bulk models. Overall the manuscript needs more clarification of the results and better explanation of the impacts of the results.
We have substantially modified the manuscript in order to clarify the discussion and to provide better explanations.

Major comments: Condensation and evaporation will affect the dynamics of the simulation so why not use a kinematic framework similar to that used by Morrison and Grabowski, 2007 where microphysics does not feedback into the dynamics? Have variables such as updraft speed checked for the simulations to ensure that the dynamics are in fact similar between the two models?
We have checked, and the mean updraft speed is very similar amongst all of the simulations. However, it should not matter if the dynamics are different. The power of the method being used to compare the simulations is that we control for all of the quantities that impact the condensation and evaporation rates (microphysical properties and saturation ratio; temperature and water vapor will also impact the rates, but they are of secondary importance) in our binning approach. Changes in dynamics will impact the frequency at which specific combinations of these quantities occur, but should not impact the mean value of the condensation and evaporation rates for each combination (each of our joint bins). Even in a kinematic framework, it can be difficult to say, for example, that average condensation rates are higher with one scheme because that scheme inherently predicts higher condensation rates, or because feedbacks from other microphysical processes resulted in more frequent occurrences of high condensation rates. Our method removes the issues associated with changes in the frequency of occurrence of specific conditions and allows us to directly compare the behavior of microphysical processes predicted by the different schemes.

More explanation needs to be given in the discussion especially in explaining how condensation and evaporation work in both bin and bulk models and why the difference in results (Fig. 5) between condensation and evaporation. In general the conclusions are confusing (especially point 1 and 2) and need to be rewritten.
The analysis, results, and conclusions have been substantially rewritten in order to clarify our

arguments and make the paper more accessible to all readers.

Only one value of the shape parameter was used for the bulk model. Do different values of the shape parameter provide better or worse comparison to bin condensation rates?
Thank you for this question. Different values of the shape parameter do change the comparison to the bin condensation and evaporation rates. Additional simulations are now included in the analysis in order to strengthen the conclusions in this regard

Does using a variable shape parameter as described in Fig. 1 lead to better results compared with bin?

The RAMS code is structured in such a way that we cannot try a variable shape parameter. However, we believe that using an appropriate diagnostic equation for the shape parameter could lead to an improved comparison.

Minor comments:
Line 27: suggest adding bulk model references
Khain et al. (2015) provide a comprehensive list of 37 bulk schemes and 22 bin schemes that have been developed, and the readers are referred to this paper for more information.

Line 28: should be “mass mixing ratio” and “total number mixing ratio”
Thank you, we have made the change.

Line 29: remove “typically”
It has been removed.

Line 31: what mixing ratio? Mass mixing ratio?
It can be either, but typically it is the mass mixing ratio. This has been specified now.

Line 37: remove “simulations with”
“Simulations with” is necessary for consistency with “benchmark simulation” earlier in the sentence.

Line 42: remove “both liquid- and ice-phase”
It has been removed.

Line 46: what do you mean by value? There is value in how computationally cheap bulk models are.
We mean predictive value and this is now explicit within the manuscript.

Line 66: explain why the third function is in total disagreement. What assumptions lead to this disagreement.
We mean that G98 shows an increase in the shape parameter as the number concentration increases whereas RL03 and MG07 show a decrease. All relationships are based on observational data. G98 bases their relationship on data from Simpson and Wiggert (1969), MG07 bases their relationship on data from Martin et al. (1994), and RL03 bases their

relationship on field campaign data compiled by Liu and Daum (2002). This is now clarified in the manuscript.

Line 79: suggest new word choice for “disagreement”
We have substituted “discrepancies”.

Line 91: explain the liquid implementation here, get rid of the appendix and get rid of the ice implementation discussion.
We agree that the appendix includes some information that is irrelevant for the present study, but we include it in order to provide a complete description of the SBM implementation in RAMS, as this is the first time that this implementation has been described in the literature.

Line 96: Walko (2000a) or Walko (2000b)?
Walko et al (2000b)

Line 96: Eq. 6 is not in Walko 2000
We are confused by the reviewer’s comment. We have double-checked and Eq. 6 in Walko et al. (2000b) is indeed the equation we are referencing.

Eq. 2: What are the units of G? Is r_c a mixing ratio or mass concentration?
Units of G are kg m^{-1} s^{-1} and it is a mass mixing ratio. These details are specified in Table 1.

Line 113: The ventilation coefficients could be set to 1 in both models to see their impact.
Yes, true, but we believe that the difference in ventilation coefficients is of secondary importance and we do not wish to investigate this level of detail here.

Line 129: what model time period are the results from? And how long does it take for the clouds to spin up?
Clouds appear after about 4.5 hours of simulation and clouds existing at any time in the simulation are used for analysis.

Line 133: suggest “homogeneously in the horizontal direction.”
This has been changed.

Line 141: define relative humidity
This is now included.

Line 169: suggest “in order to better compare...”
This has been changed.

Line 173: do you mean S-ND bins or bin-model bins
This is no longer relevant within the revised text.

Line 200: why does the RDB scheme predict higher condensation rates for low integrated diameter values? I suggest showing some bin and bulk distributions to explain the discussion from lines 199-203

This part of the discussion has been removed in the revised text.

Line 210: can you explain what it is about evaporation versus condensation that leads to the better evaporation rate comparison between the two schemes? How does the bin distribution change during evaporation versus condensation?
It is simply that the shape parameter value chosen for use in the RDB simulations (4) more closely matches the mean value of the best-fit shape parameter from evaporating cloudy points (~4) in the SBM simulations than the best-fit shape parameter from the condensing cloudy points (~7). If we instead run the RDB simulation with the shape parameter set to 7 (instead of 4), then the comparison becomes better for condensation. Physically, we expect a lower shape parameter (wider distribution) for evaporating size distributions. During condensation, the large droplets increase in diameter slowly whereas the small droplets increase in diameter quickly and thus the size distribution narrows (droplets become more similar in size). During evaporation, the same differences in diameter growth rates lead to a widening of the size distribution.

Line 221: suggest “larger shape parameter”
No longer relevant.

Line 232: why use the first 15 bins? What are the other bins used for and how many bins are there?
There are 18 additional bins with water drops having raindrop-sized diameters. We are only interested in the cloud droplets, so these additional 18 bins are not used for the analysis.

Fig. 4: suggest doing fits of the data points for better analysis
Yes, this is a good suggestion. However, we do not include these type of plots in the revised manuscript.

Line 262: The 1600 simulations cover a larger area in integrated diameter space but not supersaturation space. This should be pointed out.
In our new analysis, we group data by number mixing ratio and diameter separately. The same comment that the reviewer makes is applicable to the number mixing ratio, and this point has been made clear.

Line 268: suggest changing the word “startling”
No longer relevant.

Line 298: The rates are similar, but there is a lot more spread in the data. Statistics on the data would help here.
Standard deviation values are now included in the analysis in order to quantify the spread.

Line 300: What are you using to base the fact that a gamma distribution is a good assumption for cloud droplets? Is it because the bulk model with an assumed gamma distribution predicts condensation rates fairly well compared to a bin model? If so this should be explained.
Yes, this is the reason. This is hopefully better explained in the manuscript now.

Conclusion point 2: Just state the most important variables that determine differences between bin and bulk condensation rates. Don’t worry about stating what is not important (f and G) unless it is surprising.

This point has been removed.

Conclusion point 4: There are other reasons to use sub-stepping in bin models. Suggest removing point 4.

We agree that this point should be removed.

Line 318: condensation rates become less important when riming rates are large. Also ventilation can be large for hail. This may not matter or be relevant for certain other hydrometeor types.

This sentence has been removed.

Table 1: G_RDB should read “Terms to account...” This term also accounts for vapor diffusion.

Agreed. This has been modified appropriately.

r_c should be mass mixing ratio; saturation ratio should be defined

Yes, thank you.

Fig. 5 suggest putting a line through condensation rate ratio = 1

This figure has been removed.

References:

Igel, A.L. and S.C. van den Heever, 2016a: The importance of the shape of cloud droplet size distributions in shallow cumulus clouds. Part I: Bin microphysics simulations. Accepted pending revision at *J. Atmos. Sci.*

Igel, A.L. and S.C. van den Heever, 2016b: The importance of the shape of cloud droplet size distributions in shallow cumulus clouds. Part II: Bulk microphysics simulations. Accepted pending revision at *J. Atmos. Sci.*

We would like to thank all three referees for taking the time to review our manuscript. All referees felt that the manuscript was confusing, and we have substantially revised the manuscript to address these concerns, including a modified methodology, new figures, and clearer discussion. The basic conclusions have not changed, but we feel that they are now better explained and better substantiated. Responses to specific comments are below.

C. R. Homeyer

chomeyer@ou.edu

Received and published: 24 March 2016

Disclaimer: This is a summary of a group peer review exercise in my senior undergraduate research class at the University of Oklahoma. 2 instructors and 36 students participated in this review, which we hope the authors find beneficial.

What an excellent class exercise! We thank you for your comments and hope that the class was able to benefit from the review as well. In our revisions, we have substantially modified the description of the methods, figures, discussion, and conclusions in a sincere effort to clarify the manuscript thus making it more accessible to all readers.

The authors present an analysis contrasting condensation rates predicted by two classes of microphysics parameterizations in a numerical model: bin and bulk. They argue that, even for objectively equivalent conditions, the condensation rates (which depend primarily on the size of a cloud particle) differ. It is suggested that the chosen shape parameter of the assumed drop size distribution in the bulk microphysics scheme accounts for the disparity.

Overall, we find the paper to often be difficult to read, the discussion to be misleading and/or vague, and the analysis to be incomplete. These findings are supported by numerous general and specific comments outlined below.

General comments:

1. Readability: Defining variables in a table rather than immediately following their introduction in the text negatively impacts readability. We recommend changing this throughout the paper. In addition, the text switches between tenses on several occasions, there are numerous lengthy sentences, and on multiple occasions conclusions are given without reasoning. Several of these instances are identified in the specific comments below.

We now define the variables immediately following the equations. Specific comments regarding readability that appear below have all been addressed. Special attention has been paid to tense in order to make it consistent throughout.

2. It might be good to test for a larger variety of aerosol concentrations (more than three) before reaching conclusions.

Since the three aerosol concentrations that we tested all behaved in approximately the same way, we don't believe that testing of additional concentrations would provide more information. However, we do now include additional bulk simulations with different cloud droplet shape parameters. These tests have helped to strengthen our conclusions.

3. A more elaborate discussion/explanation of the differences between bulk and bin schemes in the introduction is needed to improve accessibility for readers with less cloud physics and/or

modeling expertise.

Some additional explanation has been added. However, we recommend reading Khain et al. (2015) for a much more thorough description of the two types of schemes. This review article is also referenced in the manuscript.

4. Model design: There were several choices in the model design that were not well qualified (model resolution, Harrington radiation scheme, land surface model, vegetation type, etc.). What is the significance and/or reasoning for making these choices?

More reasoning is now provided. Fine horizontal and vertical spacing was used in order to well resolve the cumulus clouds and their microphysical structure. Land surface and vegetation choices were made in order to most closely resemble the ARM SGP site. A radiation scheme was necessary in order to allow the boundary layer to develop.

5. The value of the best-fit parameter could not be determined before condensation occurred. Why? If bin values are known (which they must be to proceed with the bin scheme) then it seems these could be easily output and used to compute a fit. If it is not expected to have large impacts, then what magnitude could be expected?

The values are certainly known by the model before condensation, but only the values after condensation were written to files and available for our analysis. We believe that this assumption has only small impacts on the results and conclusions.

6. The Discussion and Conclusions section (though somewhat confusing) claims that the cloud droplet size distribution shape is the most important factor for agreement in condensation rates between bin and bulk schemes, but it also states that current assumptions of the size distribution shape are adequate. What are the broader impacts of this study? Should parameterizations be changed or not?

We mean that assumptions of a gamma distribution function in general are adequate, but that in order for the gamma distribution to be useful, we need better knowledge of the shape parameter that appears in this distribution function. In order to obtain a better shape parameter, we need to either move to triple-moment schemes, or find better ways to parameterize it from observations. The discussion and conclusions have been substantially modified in an effort to clarify the points being made.

7. The differences found between the simulations with the bin and bulk schemes are argued to be related to the shape of the drop size distribution. However, a double moment bulk microphysics scheme with a constant shape parameter was chosen (after arguing for the importance but unknown relationship between cloud droplet concentration and shape parameter in the Introduction). Aren’t the results shown here largely generated by this choice? Is it better (and possible) to use this analysis to determine which assumed relationship in previous parameterizations is appropriate?

Yes, additional analysis shows that the G98 relationship is the most appropriate of the three presented. This analysis appears in a separate paper, Igel et al. 2016a, which has been accepted pending revision. If we had used this relationship in our bulk simulations, then the comparison may indeed have been more favorable. We found however that while the G98 relationship is the best, it is only appropriate for a small range of aerosol concentrations.

Specific Comments:
Line 1: Change to '. . .of the Gamma Function Shape Parameter. . .'
Done.

Line 15: Omit 'does'
This word is necessary for the sentence.

Line 22-23: Suggest rewording. "since shape parameter can have a large impact. . ."
We were trying to avoid the term "shape parameter" in the abstract in order to make the abstract more understandable to a wide audience.

Line 22: Please specifically explain how the paper is important, rather than state that it 'may be' important.
'May be' has been changed to 'is'.

Line 40-41: The word 'plagued' implies a problem that should probably be identified specifically via reference to appropriate literature. In what sense do 'predefined ice habits' pose these issues?
More explanation and a reference to Khain et al. (2015) are now included. Predefined ice habits do not always appropriately describe real-world ice habits which smoothly transition between habit types.

Lines 44-46 and 53-55: Awkward sentence structure.
Thank you for the comment.

Line 54: Omit comma after 'is'
Done.

Line 61: Need to explain why this point is "clearly an outlier". The shape parameters are subject to the pitfalls of fitting a uni-modal, parametric function to a variety of histograms that don't necessarily conform to the shape of a gamma distribution. Furthermore, it isn't made clear that there exists some single distribution of which all these points should be considered 'realizations'.
It is unclear why the outlier exists. The value was calculated by Miles et al. (2000) and reported in their Table 1 based on Figure 3 in Korolev and Mazin (1993). It is possible that is an error in calculation. A value of 44.6 would indicate a rather narrow distribution, and visual inspection of Figure 3 does not suggest that the observed distributions were particularly narrow.

Line 64-65: Remove 'also' in consecutive statements.
Done.

Line 69-70: Change to 'to accurately model'
Done.

Line 81-85: Awkward, long sentence.
It has been split into two.

Line 89: Omit comma following reference.

Done.

Line 113: The differing formulations should be discussed and justified, even if only briefly.
We do not feel that the different formulations need to be justified as the formulations were not our choice, but rather the choice of the scheme developers.

Lines 126-127: “The wider range of thermodynamic conditions make the conclusions of this study more robust.” How so?
The results are not specific to a narrow range of thermodynamic conditions and hence are more applicable for a wide range of meteorological situations.

Line 131: Define ARM SGP.
Done.

Line 133: Suggest revising “horizontally homogeneously” to “homogeneously in the horizontal dimension” here and similarly elsewhere.
Done.

Line 151-154: It would be good to give a reference to show that these values encompass a variety of continental and maritime regimes. Remove ‘more’.
Thank you for the suggestions.

Line 162-164: Unclear. Also, single quotes around ‘approximately proportional’.
We mean approximately linearly proportional.

Line 166-167: Suggest replacing ‘nevertheless’ with ‘however’ and italicizing ‘can’ in
Thank you for the suggestion.

Line 167. Suggest replacing ‘doesn’t’ with ‘does not.’
Done.

Line 186: Comma after ‘therefore’
Done.

Line 191-193: Split into two sentences
Removed.

Line 192: Spelling error: “increases”
Done.

Line 197: Switch ‘easily’ and ‘compare’
This would result in a split infinitive.

Line 317-318: Why should conclusion hold for other hydrometeor types? Ice particles, for example, have more complicated vapor growth processes that ultimately depend on both particle

shape and environmental characteristics.
This sentence has been removed.

Line 201: Clarify that one needs to focus on shape parameters from 0-5 to see the difference between RDB/SBM1600 results and the others. Also would be good to not that this is the same regime where previous assumptions for shape parameter behavior diverge (i.e., Figure 1).
No longer relevant given the broader revisions to the text.

Line 205: Should be ‘Fig. 4 d-f’
Thank you. This figure has been removed.

Line 206: Change ‘worst’ to ‘strongest’ or ‘largest’
Removed.

Line 208-209: This statement bares some explanation and maybe a citation. Also, if this is the most common case, why is it not shown in evaporation figures?
We are unsure what the reviewer is suggesting. This sentence is a statement of our results. Regardless, the figure and associated discussion has been removed.

Line 209: Comma after ‘Thus’
Removed.

Line 210: Change ‘between’ to ‘of’ and remove ‘do’
Removed.

Line 223: Omit comma after ‘distributions’
Thank you for the suggestion.

Line 229: missing period
Thank you.

Line 242-245: Why is that not expected? Seems ‘reasonable’ in most cases, but the a gamma distribution shape parameter fit to a very flat, broad distribution would seem subject to very rapid changes due to modest movements of probability left or right. It would be good to elaborate a bit more.
Yes, we agree that there may be some cases when the shape parameter does change rapidly in one second, particularly when the condensation or evaporation rate is particularly large and the distributions are broad (low shape parameters). Cloudy points with best-fit shape parameters less than 1 are not included in the analysis. This is discussed in more detail now in the revised manuscript.

Line 244: Comma after ‘step’, omit ‘thus’.
The sentence has been split in two.

Line 248-254: The ‘theoretical’ ratio needs clarification. It is not clear what is meant by a bin scheme ‘predicting’ a gamma distribution. Evaporation and condensation rates can be predicted based on a histogram conforming to a gamma distribution of particular shape parameter. If this is what is implied, then rewording is needed.

The explanation of the theoretical ratio has been substantially expanded and is reproduced below. Note that in the revised paper, we group points by S, N, and $\bar{D}$ rather than S and $N\bar{D}$.

Revised explanation:

The shape parameter term in Eq. (2) (hereafter f_{NU}), which is equal to $\nu\left(\frac{\Gamma(\nu)}{\Gamma(\nu+3)}\right)^{1/3}$, can be evaluated for each joint bin in the S, N, and $\bar{D}$ phase space for all simulations. In the case of each BULK simulations, the value of f_{NU} is the same for every joint bin since the value of f_{NU} is uniquely determined by the choice of the shape parameter value for each BULK simulation. For the BIN simulations, f_{NU} can be calculated using the best-fit shape parameters. Unlike for the BULK simulations, the value of f_{NU} for the BIN simulations will vary amongst the joint bins since the best-fit shape parameter is determined from the freely evolving cloud droplet distributions that are predicted by the BIN microphysics scheme. We can use the values of f_{NU} in our comparison of the condensation and evaporation rates to account for the fact that the best-fit shape parameters in the BIN simulations will often be different from the single prescribed value in the BULK simulations. Specifically, in our analysis, we adjust the mean condensation and evaporation rates (C) for each joint bin from the BULK simulations in the following way:

$$C_{BULK,modified} = C_{BULK,original}\frac{f_{NU,BIN}}{f_{NU,BULK}}$$

By doing so, we find the condensation and evaporation rates that the BULK simulations would have had if they had used the same value of the shape parameter that best characterized the cloud droplet size distributions that were predicted by the BIN simulations.

Line 253: Omit ‘specifically’

Removed.

Line 264: Comma after ‘Therefore’

Removed.

Line 278: Move comma from after to before ‘removed’

Removed.

Line 286: Comma after ‘study’, suggest changing ‘conducted a comparison’ to ‘compared’

Thank you for the suggestion.

Line 300-302: Based on the preceding sections, the gamma distribution has not been rigorously shown to be ‘good’, in that there is no exact standard set forth with which to judge ‘goodness’. Also, nothing is offered with which to compare this estimator. There might be a better parametric form and certainly a semi-non-parametric form could be devised that would beat the max. likelihood fit of the gamma function in almost all cases. Not that one needs to test non-parametric forms in this paper, but the exact nature and limits of performance expectations needs to be defined in such a way that other options are reasonably set aside.

We now include a measure of “goodness” for the gamma distribution fits, and find that in general the gamma distribution performs quite well. We agree that there may often be a different PDF that may fit the bin model cloud droplet size distributions better, but as most bulk microphysics schemes use a gamma distribution, this is the distribution that we are interested in studying in the current manuscript. It may be of interest to look at other parametric and non-parametric forms in a separate study.

Line 313: Commas after 'time step' and 'thus'
Removed.

Line 317: Suggest not starting with 'And'. Also, the 'them' that has not been explored apparently refers to 'other hydrometeors', that doesn't work well since one doesn't really explore hydrometeors. Suggest rewording.
Removed.

Line 320: Reword. "presented a novel method. . ." instead of "presented here. . ."
Done.

Line 445: Figure 1. It is not clear that interpolation between data points is appropriate. See comments on Line 61.
No interpolation has been performed in Figure 1. Colored lines connect values that were reported from the same study.

Line 446: Number disagreement. If a clear reason to assume functionality is demonstrated, then it should read "Shape parameter as a function of. . .", that is, omit "values"
We did not intend to imply that there is a definite functionality, only to indicate that shape parameter is on the y-axis and droplet concentration is on the x-axis. This is now clarified in the manuscript.

Line 455: Figure 2 caption. Should include date, time and station of the soundings from which profiles were adapted
This figure has been removed.

Line 459: Number disagreement. Should be "rates as functions. . ."
This figure has been removed.

Line 466: Figure 5. It would be interesting to see some 'quantile' brackets, R2 values, etc. to quantify 'closeness' of fit. It isn't clear from the figure (packed with dots) where the greatest concentration of dots is, other than the general shape of the opaque area. . . some areas may be 'more opaque' than others.
This figure has been removed. In the revised paper, we include standard deviation values in order to quantify the spread.

References:

Igel, A.L. and S.C. van den Heever, 2016a: The importance of the shape of cloud droplet size distributions in shallow cumulus clouds. Part I: Bin microphysics simulations. Accepted pending revision at *J. Atmos. Sci.*

Igel, A.L. and S.C. van den Heever, 2016b: The importance of the shape of cloud droplet size distributions in shallow cumulus clouds. Part II: Bulk microphysics simulations. Accepted pending revision at *J. Atmos. Sci.*

Relevant Manuscript Changes:

1. Most changes were made to improve the readability of the manuscript and to provide better explanation of the analysis methods being used and the interpretation of the results.
2. Figures 2-5 and Table 2 and accompanying discussion are new, and the previous Figures (with the exception of the current Figure 1) have been removed. The new figures address many of the same points that were being made in the original manuscript, but we feel that the new figures are easier to interpret.
3. The revised discussion includes sections related to the appropriateness of assuming a gamma PDF and more in-depth analysis of evaporation.

The Role of the Gamma Function Shape Parameter in Determining Differences between Condensation Rates in Bin and Bulk Microphysics Schemes

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Abstract. The condensation and evaporation rates predicted by bin and bulk microphysics schemes within the same model framework are compared in a novel way using simulations of non-precipitating shallow cumulus clouds. Despite fundamental disparities between the bin and bulk condensation parameterizations, the differences in condensation rates are predominantly explained by accounting for the width of the cloud droplet size distributions simulated by the bin scheme. The bin scheme does not always predict a cloud droplet size distribution that is well represented by a gamma distribution function (which is assumed by bulk schemes); however, this fact does not appear to be important for explaining why the two scheme types predict different condensation and evaporation rates. The width of the cloud droplet size is not well constrained by observations and thus it is difficult to know how to appropriately specify it in bulk microphysics schemes. However, this study shows that enhancing our observations of this width and its behavior in clouds is important for accurately predicting condensation and evaporation rates.

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1. Introduction

Bin and bulk microphysics schemes are both popular approaches for parameterizing subgrid-scale cloud processes as evidenced by the large number of schemes that have been developed. Tables 2 and 3 in Khain et al. (2015) summarize the characteristics of dozens of microphysics schemes, and discuss in detail the fundamental principles of these two basic types of schemes. Briefly, in double-moment bulk schemes, the mass mixing ratio and total number mixing ratio for predefined hydrometeor species are 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 mass mixing ratio and/or the number mixing ratio is predicted for each bin.

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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 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 subject to many of the same issues as bulk schemes, such as the use of predefined ice habits (which may not always appropriately describe real-world ice) and the conversion between ice types (the real atmosphere does not have strict categories for ice), rendering them not necessarily more accurate (Khain et al. 2015). Regardless, bin schemes are much more computationally expensive since many additional variables need to be predicted. As a result, bin schemes are used less frequently than bulk schemes, and are not currently utilized in any operational models. It is

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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 predictive value is added by using a bin instead of a bulk microphysics scheme. Furthermore, comparison of process rates in bin and bulk schemes could help to identify ways in which to improve bulk schemes.

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

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

where ν is the shape parameter, N is the number mixing ratio, D is the diameter, and D_n is a scaling diameter (the inverse of D_n is often called the slope parameter). All symbols are defined in Table 1 for reference. 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.

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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 between the shape parameter and 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 additionally shows that two of the proposed functions relating these two quantities are similar (RL03 and MG07), but that the third function (G98) exhibits an opposite trend compared with these first two.

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Furthermore, using appropriate values of the shape parameter may be necessary to accurately model 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 Figure 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 Figure 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 discrepancies 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

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differences between the two schemes. 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 (BULK) (Saleeby and Cotton, 2004) and the Hebrew University spectral bin model (BIN) (Khain et al., 2004). The Hebrew University spectral bin model is newly implemented in RAMS. Details about the implementation can be found in Appendix A.

In the BULK microphysics scheme, condensation/evaporation is treated with a bulk approach. Cloud droplet size distributions are assumed to conform to a gamma probability distribution function (PDF) 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 BIN condensation/evaporation equation shown below. Specifically, the BULK condensation/evaporation equation can be written as

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

The BULK scheme uses this equation for all cloud species, such that the supersaturation is explicitly predicted; a saturation adjustment scheme is not used for cloud water.

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

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

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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). In both equations, r_c is the cloud mass mixing ratio, f_v is the ventilation coefficient, G is a term that accounts for latent heating, vapor diffusion and heat diffusion, S is the saturation ratio, and t is time. The saturation ratio is defined as the ratio of the water vapor partial pressure to the saturated water vapor partial pressure. More details are given in Table 1.

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

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- In the BIN, 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 BULK scheme.
- The time step integration is performed semi-analytically in the BIN with multiple sub-time steps rather than implicitly as in the BULK scheme.

Deleted: <#>The formulation of the ventilation coefficients and of G_{BULK} and G_{BIN} are different, though the details will not be discussed here.

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 on the analysis. 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.

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The wider range of thermodynamic conditions make the conclusions of this study more robust. The simulations were the same as those described in Igel et al. 2016a-b. They were run with RAMS and employed 50m horizontal grid spacing and 25m vertical grid spacing over a grid that is 12.8 x 12.8 x 3.5 km in size. Such fine grid spacing was used in order to well resolve the cumulus clouds and their microphysical structure. The simulations were run for 9.5 hours using a 1s time step. Clouds appeared after about 4.5 hours. The simplified profiles of potential temperature, horizontal wind speed, and water vapor mixing ratio based on an Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) sounding from 6 July 1997 at 1130 UTC (630 LST) presented in Zhu and Albrecht (2003) (see their Fig. 3) were used to initialize the model homogeneously in the horizontal direction. Random temperature and moisture perturbations were applied to the lowest model level at the initial time in order to initiate convection.

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 the saturation ratio was changed in the BULK scheme to make it the same as the calculation in the BIN. The BIN does not include a parameterization for aerosol dry deposition, so this process was turned off in the BULK scheme. Finally, the regeneration of aerosol following droplet evaporation was deactivated in both microphysics schemes. Aerosol concentrations were initialized homogeneously in the horizontal and vertical directions. Aerosol particles did not interact with radiation.

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Deleted: 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.

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Five simulations were run with the BULK scheme and three with the BIN scheme. Since the relationships in Figure 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. These BULK simulations used a shape parameter value of 4. Two additional BULK simulations were run with an aerosol concentration of 400 cm^{-3} and shape parameter values of 2 and 7. These values were chosen based on previous analysis of the BIN simulations in Igel et al. 2016a. The BIN simulations will be referred to by the microphysics scheme abbreviation and the initial aerosol concentration, e.g. BIN100, and the BULK simulation names will additionally include the value of the cloud droplet shape parameter, e.g. BULK100-NU4.

4. Results

4.1 Instantaneous Condensation Rates

In order to compare directly the condensation rates predicted by the BULK and BIN microphysics schemes, it is necessary to evaluate these rates given the same thermodynamic and cloud microphysical conditions. The BULK condensation equation (Eq. (2)) is approximately linearly proportional to four quantities: S, N, $\bar{D}$, and ν. We say approximately proportional since the presence of the ventilation coefficient (which itself depends on $\bar{D}$ and ν) makes these factors not truly proportional to the condensation rate. In the BIN scheme, among these four variables, the condensation rate is only explicitly proportional to S, and is not explicitly proportional to N, $\bar{D}$, or ν (Eq. (3)) since the BIN scheme does not make assumptions about the functional form of the size distribution. If it is assumed nevertheless that the BIN size distributions *can* be described

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by some probability distribution function (which does not necessarily have to be a gamma distribution), then we would still expect the BIN scheme condensation rate to scale linearly with N and $\bar{D}$. Therefore, in order to best compare 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, N, and $\bar{D}$ that existed at the start of the condensation/evaporation process and were averaged in each joint phase space bin. (Note that these phase space bins are not the same is the hydrometeor distribution bins.) That is, all points with the same S, N, and $\bar{D}$ were grouped and the average condensation or evaporation in each group of points was calculated. Saturation ratio bin widths of 0.1 or 1 were used where the cloud was supersaturated or subsaturated, respectively. For $\bar{D}$, bin widths of 1 μm were used. For N, the bin width depended on the initial aerosol concentration of the simulation: bin widths of 2.5, 10, and 40 mg^{-1} were used for simulations with an initial aerosol concentration of 100, 400, and 1600 mg^{-1}, respectively. The output from the dynamical 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 from additional model output, and since microphysics was 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 calculated from the model output.

Note that the aerosol activation parameterizations in the BULK and BIN microphysics were not the same, and hence the number of nucleated cloud droplets was not the same. This impacted the number of data points within each joint S, N, and $\bar{D}$ phase space bin. However, we are primarily concerned with the average condensation rate in each phase space bin, and the average value should not be impacted by the number of data points within a phase space bin, provided that the

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The average condensation rate in each S, N, and $\bar{D}$ joint phase space bin was calculated for all simulations. All points where the cloud mixing ratio before condensation was greater than 0.01 g kg^{-1} and the cloud droplet number mixing ratio was greater than 5 mg^{-1} were included in the analysis. In addition, grid points with relative humidity between 99% and 101% *after* condensation or evaporation were excluded. The condensation or evaporation rates at these points were limited by the supersaturation or subsaturation, respectively, and thus the rates were not highly dependent on the droplet characteristics. Since we are interested in understanding how the different representations of droplet distributions impact the condensation and evaporation rates, we do not include these points in our analysis. Finally, as stated above, phase space bins with fewer than 50 data points were discarded. Figure 2 shows an example of the average condensation and evaporation rates in the phase space bins for one simulation. As is seen in Figure 2, there is a smooth transition to higher condensation rates as the saturation ratio increases, and to higher condensation ($S \geq 1$) and evaporation ($S<1$) rates as the droplet diameter or number mixing ratio 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, we calculate the logarithm of the BULK to BIN condensation and evaporation rate ratios (these

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values will be referred to as ‘ln(ratios)’) for five pairs of simulations. Specifically, BULK400-NU2, BULK400-NU4, and BULK400-NU7 are all compared to BIN400, while BULK100-NU2 is compared to BIN100 and BULK1600-NU2 is compared to BIN1600. Histograms of this ratio for all pairs of simulations are shown in Figure 3a-b and Figure 3e-f. This set of ln(ratio) histograms will be referred to as ORIG. The data have been separated into subsaturated (evaporating) and supersaturated (condensing) points. Positive values indicate that the rates in the BULK scheme are larger, and negative values indicate that the rates in the BIN scheme are larger. Values of ± 0.1 (± 0.2) correspond to about a 10% (20%) difference.

First we examine the impacts of increasing aerosol concentrations on evaporation and condensation rates for BULK simulations with the same shape parameter. Figures 3a-b show the histograms of the condensation and evaporation rate ln(ratios) for pairs of simulations with a cloud droplet shape parameter of 4 but with differing initial aerosol concentration. Table 2 additionally lists the standard deviation associated with each histogram. Figure 3a reveals that in general the condensation rate is higher in the BIN scheme simulations as indicated by the more frequent negative ln(ratios), whereas the evaporation rates are more similar between the two scheme as indicated by the most frequent ln(ratios) being equal to 0. For the simulation pair with an initial aerosol concentration of 1600 cm^{-3}, there is a long tail of positive ln(ratio) values. As a result, this pair of simulations has the highest standard deviation of the ln(ratio) values of all simulation pairs (Table 2a).

We now examine the impacts of variations in the shape parameter for a constant aerosol concentration. Figures 3e-f show the histograms of condensation and evaporation rate ln(ratios)

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for the three BULK400 simulations that have different values of the cloud droplet shape parameter. All three BULK400 simulations are compared to the BIN400 simulation. For both condensation and evaporation, the ln(ratios) increase as the cloud droplet shape parameter used in the BULK400 simulations increases. For the BULK400-NU2 simulation, the condensation and evaporation rates are frequently 20% lower than the BIN400 rates or more, whereas, for the BULK400-NU7 simulation, the condensation rates compared to the BIN400 simulation are most frequently very similar (ln(ratio) near zero). Thus the value of the cloud droplet shape parameter chosen for use in a simulation is clearly important for determining how well a bulk microphysics scheme compares to a bin microphysics scheme in terms of predicted condensation and evaporation rates.

4.2 Impact of the Shape Parameter on Condensation and Evaporation

Fortunately, we know theoretically how the cloud droplet shape parameter will alter condensation and evaporation rates and this dependency can be accounted for in our comparison of the two microphysics schemes. The shape parameter term in Eq. (2) (hereafter f_{NU}), which is equal to $\nu\left(\frac{\Gamma(\nu)}{\Gamma(\nu+3)}\right)^{1/3}$, indicates that when a gamma PDF is assumed, the condensation rate is proportional to the shape parameter ν such that a higher shape parameter results in higher condensation rates. The BIN scheme makes no assumptions about the size distribution functionality. However, in order to characterize the predicted BIN cloud droplet size distributions, and to facilitate the comparison of the BIN and BULK condensation rates, we assumed that the predicted BIN size distributions are gamma PDF-like and found the best-fit gamma PDF parameters (see Eq. (1)) for the cloud droplet size distributions at every cloudy grid point in the BIN simulations. (We could just have easily fitted another PDF to the BIN

Deleted: For evaporation (Fig. 3d-f), the BULK and BIN 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.

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distributions, but chose the gamma PDF since that is what is assumed by most bulk schemes, including the one being used in this study. We examine the appropriateness of this choice in section 4.3.1.) We then evaluated the mean value of f_{NU} using these best-fit shape parameters for each joint bin in the S, N, and $\bar{D}$ phase space.

In order to find the best-fit shape parameters, we defined cloud droplets as belonging to one of the first 15 bins of the BIN liquid array (the remaining 18 bins contain raindrops), which corresponded 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 used the maximum-likelihood estimation method and found best-fits that minimize the error in the total number mixing ratio. Using this method, the size distributions were first normalized by the corresponding total number mixing ratio, leaving only D_n and v as free parameters of the distribution (Eq. 1).

Note that while we could determine the values of S, N, and $\bar{D}$ that existed before condensation occurred, we could not determine the value of the best-fit shape parameter for this time because the change in mixing ratio of each bin was 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 was not expected that the best-fit shape parameter would change much in one time step in most cases. The exception may be for very broad distributions characterized by low shape parameters. In part due to this concern, cloudy points with best-fit shape parameters less than 1 are not included in the analysis. Overall, the impact of

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using the post-condensation shape parameters is not expected to have a large impact on the results presented here.

The shape parameter term (f_{NU}) can be evaluated for each joint bin in the *S*, *N*, and $\bar{D}$ phase space for all simulations. In the case of each BULK simulations, the value of f_{NU} is the same for every phase space bin since the value of f_{NU} is uniquely determined by the choice of the shape parameter value for each BULK simulation. For the BIN simulations, f_{NU} can be calculated using the best-fit shape parameters. Unlike for the BULK simulations, the value of f_{NU} for the BIN simulations will vary amongst the phase space bins since the best-fit shape parameter is determined from the freely evolving cloud droplet size distributions that are predicted by the BIN microphysics scheme. We can use the values of f_{NU} in our comparison of the condensation and evaporation rates to account for the fact that the best-fit shape parameters in the BIN simulations will often be different from the single prescribed value in the BULK simulations. Specifically, in our analysis (but not in the simulations themselves), we adjusted the mean condensation and evaporation rates (*C*) *for each phase space bin* from the BULK simulations in the following way:

$$C_{BULK,corrected} = C_{BULK,original} \frac{f_{NU,BIN}}{f_{NU,BULK}} \quad (4)$$

Note again that the value of $f_{NU,BIN}$ will be different for each phase space bin. By making this correction, we found the condensation and evaporation rates that the BULK simulations *would have had* if they had used the same value of the shape parameter that best characterized the cloud droplet size distributions that were predicted by the BIN simulations.

The ln(ratios) of the modified condensation and evaporation rates from the BULK simulations to the rates from the BIN simulations are shown in Figures 3c-d and Figures 3g-h. This set of ln(ratios) will be referred to as CORR. The most frequent value of the CORR ln(ratios) is near zero (indicating that the two schemes predict the same rate) for all simulation pairs and for both condensation and evaporation. The impact of the modification is most notable in Figures 3g-h where the histograms of the CORR ln(ratios) now nearly lie on top of one another whereas in Figures 3e-f they are clearly separated. Thus it appears that our method of accounting for the value of the shape parameter has worked well.

Furthermore, the standard deviation of the condensation rate CORR ln(ratio) histograms is decreased by about half compared to the ORIG ln(ratio) histograms (Table 2a-b). This is not the case for the evaporation rate CORR ln(ratio) histograms where the standard deviation is increased compared to the ORIG ln(ratio) histograms in four out of five simulation pairs. Nonetheless, given that all CORR histograms now have a modal value near 0, whereas this was not the case with the ORIG histograms, the shape parameter appears to be the primary reason why the condensation and evaporation rates in the two schemes do not always agree.

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4.3 Other Considerations

While the shape parameter appears to be the primary cause of the differences in condensation and evaporation rates in bin and bulk microphysics schemes, we now investigate whether any of the other factors are also important.

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4.3.1 Appropriateness of the Gamma PDF

One potential factor worth considering is that the gamma PDF is not always appropriate for characterizing the cloud droplet size distributions in the BIN simulations. The BIN microphysics scheme is capable of predicting any shape for the cloud droplet size distributions, including size distributions that may be bimodal. To assess how well our fitted gamma PDFs approximated the actual simulated cloud droplet size distributions, we calculated the normalized root mean square error (NRMSE) of the fits. An NRMSE of 1 indicates that the fit was no better than a straight line, and a value of 0 indicates a perfect fit. Figures 4a-b show cumulative histograms of the NRMSE values from the three BIN simulations for both evaporating and condensing cloudy points. Note that these are not cumulative histograms of mean values from joint bins as in Figure 3, but rather they are cumulative histograms of the NRMSE values at all individual cloudy grid points in the BIN simulations. The majority of grid points have NRSME values of 0.6 or lower which indicates that in general the gamma PDF characterizes the simulated cloud droplet size distributions very well.

We repeated the calculations of mean condensation or evaporation rate in each S, N, and $\bar{D}$ joint phase space bin for the BIN simulations, but now we only included those cloudy points with an NRMSE of 0.6 or more (those points with a poor gamma PDF fit). The phase space bins for the BULK simulations were unaltered, but did include the modification described by Eq. (4) which now used values of $f_{NU,BIN}$ based only on the high NRMSE points. The resulting histograms of condensation and evaporation rate ln(ratios) are shown in Figures 5a-b for all simulation pairs. The associated standard deviations are listed in Table 2c. This set of histograms will be referred to as CORR-POOR. For evaporation, the peaks of the CORR-POOR ln(ratios) histograms shift to positive values (Fig. 5a) indicating that the agreement between the BULK and BIN rates is degraded, although the standard deviations of these histograms are similar compared to the CORR histograms (Table 2c compared to Table 2b). The shift in peak ln(ratios) suggests that when the BIN simulations produce cloud droplet size distributions that poorly conform to a gamma PDF, the best-fit shape parameter is less useful for understanding the differences between BULK and BIN evaporation rates.

However, for condensation rates, the results are less clear. Figure 5b shows that many of the high CORR-POOR ln(ratio) histograms are still centered near 0, which indicates that the BIN and modified BULK condensation rates still agree well. Furthermore, the standard deviation of these histograms is similar to those of the CORR histograms (Table 2b-c). Unlike for evaporation, these results for condensation suggest that the fact that the BIN simulations do not predict cloud droplet size distributions that are similar to gamma PDFs is not an important reason for why the BULK and BIN schemes predict different condensation rates. It is unclear why the comparisons of condensation and evaporation rates behave so differently. This uncertainty will be explored next.

4.3.2 Fraction of Cloud Mass Evaporated

One potential reason that evaporation comparison is generally worse than the condensation comparison relates to the fractional change of mass. Specifically, the comparison may be better for situations in which only a small fraction of the total cloud droplet mass is condensed or evaporated within a time step versus a situation in which a large fraction of mass is evaporated. The reason for this is that the BIN microphysics scheme takes an iterative approach to condensation and evaporation in which many small time steps are taken. After each small time step the droplet properties are updated. When the droplet properties are changing rapidly, this approach may be important for accurately predicting the evolution of the total mass and number of cloud droplets. On the other hand, the RAMS bulk scheme takes just one step (which is equal to the full model time step length) and cannot account for rapidly changing droplet properties within the time step. Note that both approaches to the time step during condensation and evaporation could be applied to any bulk microphysics scheme, and hence the differences in condensation and evaporation due to the two approaches are not necessarily specific to differences in bin and bulk schemes. That being said, the behavior associated with each time stepping approach should be similar regardless of the specific scheme that is employing the approach.

Cumulative histograms of the fraction of cloud mass evaporated in one full time step are shown in Figure 4c for the BIN simulations. Higher fractions of mass are evaporated more frequently as the initial aerosol concentration increases. This result is not surprising given that the high numbers of cloud droplets nucleated from the high numbers of aerosol particles will induce, on average, higher evaporation rates (Eq (2) and Eq(3)) that cause a higher fraction of mass to be evaporated in one time step. Similarly, cumulative histograms of the fraction of cloud droplet mass condensed in the time step are shown in Figure 4d. Again, high fractions of cloud mass are condensed more frequently as the initial aerosol concentration increases. Overall, large fractional changes in the cloud mass are more frequent during evaporation than during condensation.

Again, the calculations of mean evaporation rate in each S, N, and $\bar{D}$ joint phase space bin for both the BULK and BIN simulations were repeated but this time with cloudy points separated by low and high mass fraction change. High evaporated mass fraction is defined as 0.25 or higher. Very few cloudy points undergoing condensation have a mass fraction change of 0.25 or higher.

Likewise, very few evaporating cloudy points in BIN100 exceed this threshold. Thus, the following analysis is only performed for the subsaturated, evaporating cloudy points for simulations pairs that include BIN400 or BIN1600.

The evaporation rate ln(ratio) histograms for the two groups (referred to as CORR-LFR and CORR-HFR) are shown in Figures 5c-d and the associated standard deviations are listed in Table 2d-e. It is immediately obvious that the two microphysics schemes behave quite differently for the case of high evaporated fractions. The standard deviation of the CORR-HFR ln(ratio) histograms are up to twice as large as those for ORIG or CORR-LFR (Table 2a,d). Furthermore, most of the CORR-HFR histograms are shifted almost entirely to the right of 0. This result indicates that when the BIN simulations evaporate a high fraction of the cloud mass in one time step, they almost always predict a higher evaporation rate than the BULK simulations when given the same initial cloud properties and relative humidity.

Finally, we found that for grid points at which a high fraction of cloud mass is evaporated, the cloud droplet size distributions predicted by the BIN simulations are more likely to fit poorly to a gamma PDF (not shown). In order to determine which effect was more important, we performed the BULK to BIN evaporation rate comparison twice more: firstly where only BIN simulation points with a high NRMSE of the fitted gamma distributions and a low fraction of cloud mass evaporated were included, and secondly with the opposite conditions where only BIN simulations points with a low NRMSE and a high evaporated fraction were included. The standard deviations of the resultant histograms are listed in Table 2f-g. In the case of high NRMSE and low evaporated fraction, the standard deviations are similar to those for CORR

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(Table 2b,f), whereas in the case of low NRMSE and high evaporated fraction the standard deviations are high and are similar to those for CORR-HFR. Thus, it seems that the occurrence of high evaporated fraction is more important for explaining poor agreement between the BULK and BIN microphysics scheme than is a poor fit of a gamma PDF to the cloud droplet size distributions simulated by the BIN scheme.

5. Conclusions

In this study we have compared the cloud 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. Two additional simulations with the RAMS bulk microphysics scheme were run with different settings for the cloud droplet shape parameter. When the condensation and evaporation rates were binned by saturation ratio, cloud droplet number mixing ratio, and mean droplet diameter, the BULK rates were on average higher or lower than the BIN rates depending on the value of the shape parameter used in the BULK simulations. Since the theoretical relationship between the shape parameter and condensation/evaporation rates is known, we adjusted the BULK rates to be those that the simulations would have predicted if they had used the same value of the shape parameter as was found by fitting gamma PDFs to the BIN droplet size distribution output. After doing so, we showed that the BULK and BIN rates were in general in much better agreement, although the condensation rates agreed better than the evaporation rates. Additional analysis supported the following conclusions:

Deleted: 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 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 BULK simulations the shape parameter is constant and has a value of 4. Therefore, specifically, the line is equal to (see the v dependency in Eq. 2). ... [1]

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Deleted: Otherwise, the BULK condensation and evaporation rates were consistently lower than those predicted by the BIN. Further analysis indicated

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Deleted: 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 BIN. A number of

Deleted: for non-precipitating continental cumulus clouds 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. When a large fraction of the cloud droplet population mass is evaporated within a model time step, the BIN scheme usually predicts lower evaporation rates than the BULK scheme. This appears to be one reason why the evaporation rates comparison is poorer than the condensation rates comparison. It is possible that the multiple sub-time steps taken by the BIN scheme may be important for accurately predicting evaporation rates in either scheme. Such a time-stepping approach could easily be implemented in a BULK scheme. This reason for discrepancy between the two schemes, however, is of secondary importance compared to the shape parameter.

Deleted: <#>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. ... [2]

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Again, it appears that *the most important factor for agreement in cloud droplet condensation rates between bin and bulk schemes is the shape* parameter *of the cloud droplet size distribution*. More effort is needed to understand the behavior of the cloud droplet shape parameter in order to improve the representation of cloud droplet size distributions in bulk microphysics schemes.

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

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, our understanding of what the most appropriate value of the shape parameter is or

Deleted: We have presented here a novel method for comparing condensation rates between any two microphysics schemes.

Deleted: and that the shape parameter value can change the condensation rate by 50% or more, how it should vary as a function of basic cloud properties is limited. More work then is therefore also needed on understanding cloud droplet distributions from observations and measurements.

Acknowledgements:

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Appendix A

Implementation of the Hebrew University BIN scheme into RAMS

While the present study is only concerned with warm phase processes, the methods to interface the Hebrew University BIN scheme with the RAMS radiation scheme (Harrington, 1997) will be described here for completeness, 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 BIN correspond directly to species in the RAMS microphysics scheme, namely, aggregates, graupel, and hail. All liquid drops are represented as one species in the BIN, 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 BIN 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 BIN ice crystal species as either pristine ice or snow. This fortuitous overlap in the ice species has allowed for the seamless integration of the BIN hydrometeor species with the RAMS radiation scheme. For each set of BIN 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.

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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. $D_n^3=\bar{D}^3\Gamma(v)/\Gamma(v+3)$
$f_{v,BULK}$, $f_{v,BIN}$	Ventilation coefficients for the BULK and BIN schemes, respectively
G_{BULK}, G_{BIN}	Term to account of the impact of latent heat release, vapor diffusion, and heat diffusion on the condensation process. See *Walko et al.* [2000] and *Khain and Sednev* [1996] for the formulations used in the BULK and BIN schemes, respectively. Units are kg m^{-1} s^{-1}.
N	Cloud droplet number mixing ratio
n	Concentration of cloud droplets per unit cloud droplet diameter interval
r_c	Cloud water mass mixing ratio
r_v	Water vapor mass 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

Table 2. Standard deviation of the ln(ratio) histograms shown in Figures 3 and 5.

	(a) Original, all data (ORIG)	(b) Corrected, all data (CORR)	(c) Corrected, high NRMSE only (CORR-POOR)	(d) Corrected, low fraction mass evaporated (CORR-LFR)	(e) Corrected, high fraction mass evaporated (CORR-HFR)	(f) Corrected, high NRMSE and low fraction mass evaporated	(g) Corrected, low NRMSE and high fraction mass evaporated
Evaporation							
BULK100-NU4/BIN100	0.032	0.025	0.025	-	-	-	-
BULK400-NU4/BIN400	0.044	0.055	0.056	0.041	0.056	0.038	0.054
BULK1600-NU4/BIN1600	0.097	0.120	0.134	0.090	0.160	0.105	0.153
BULK400-NU2/BIN400	0.041	0.054	0.053	0.053	0.046	0.041	0.055
BULK400-NU7/BIN400	0.061	0.072	0.064	0.047	0.087	0.041	0.082
Condensation							
BULK100-NU4/BIN100	0.057	0.033	0.027	-	-	-	-
BULK400-NU4/BIN400	0.056	0.027	0.035	-	-	-	-
BULK1600-NU4/BIN1600	0.057	0.033	0.032	-	-	-	-
BULK400-NU2/BIN400	0.059	0.029	0.032	-	-	-	-
BULK400-NU7/BIN400	0.050	0.026	0.023	-	-	-	-

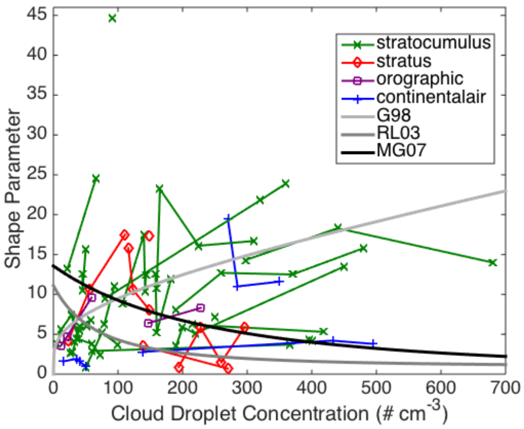

Figure 1. Shape parameter (ν) values as a function of cloud droplet number concentration as reported by Miles et al. (2000) using 16 previous studies. Values, cloud classification, and groupings are based on their Tables 1 and 2. The three solid gray lines show proposed relationships between the cloud 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.

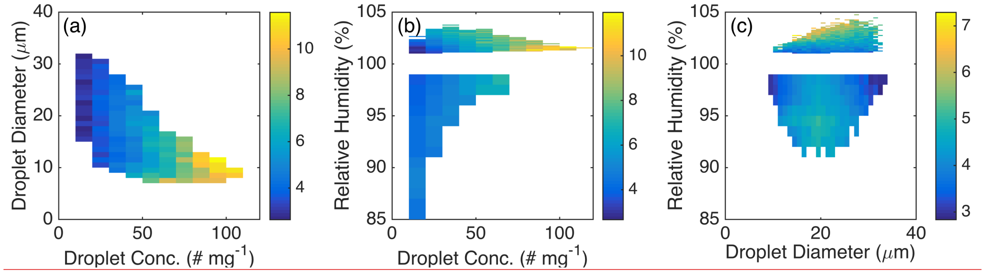

Figure 2. The average condensation and evaporation rates (g kg^{-1} s^{-1}) in joint bins from BIN400. (a) Joint bins where the relative humidity is 101-101.1% (b) Joint bins where the cloud droplet diameter is 18-19 μm. (c) Joint bins where the cloud droplet concentration is 20-21 mg^{-1}. See the text for more information about the joint bins.

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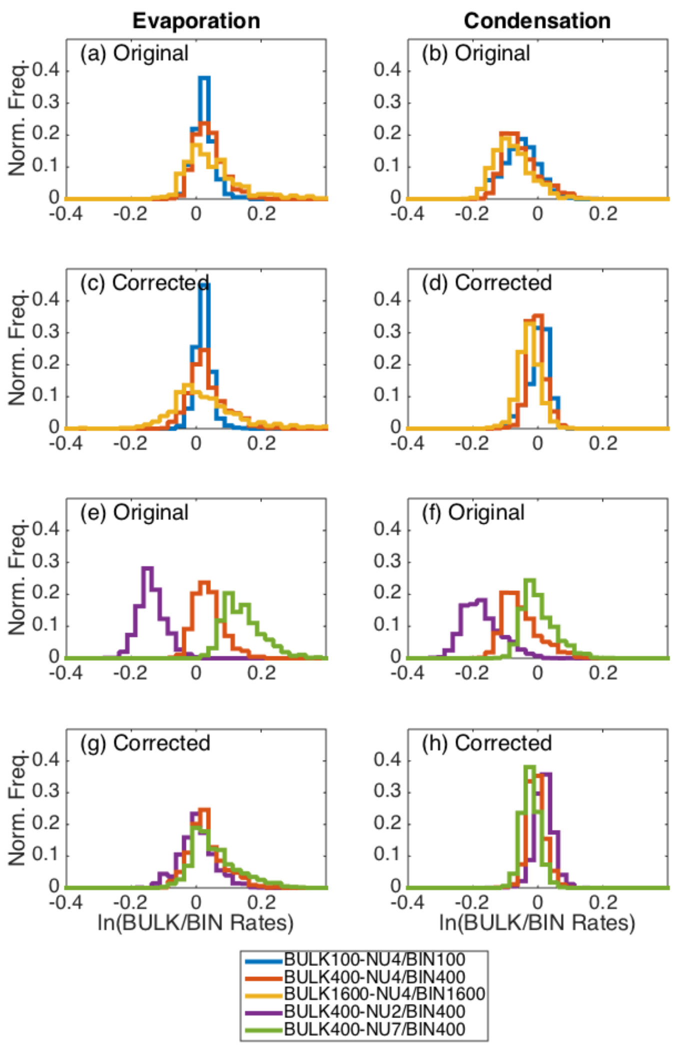

Figure 3. Normalized histograms showing the logarithm of the ratio of BULK to BIN (a, c, e, g) evaporation and (b, d, f, h) condensation rates, (a-b) and (e-f) show histograms using the original data, and (c-d) and (g-h) show histograms where the correction in Eq. (4) has been applied.

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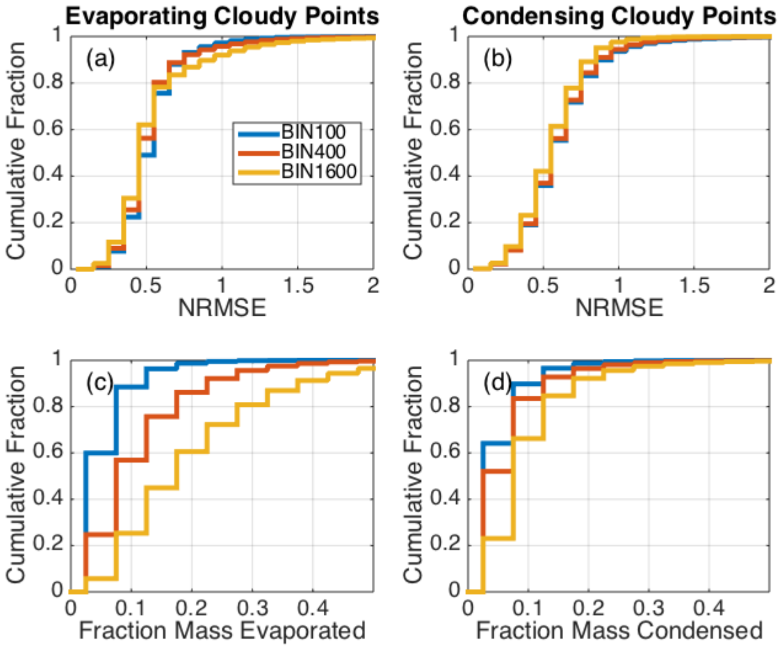

Figure 4. Cumulative histograms of (a-b) the normalized root mean square error (NRMSE) of the fitted gamma PDFs to the simulated cloud droplet size distributions in all three BIN simulations and (c-d) the fraction of cloud mass evaporated or condensed in a time step in all three BIN simulations. (a, c) show evaporating cloudy points and (b, d) show condensing cloudy points.

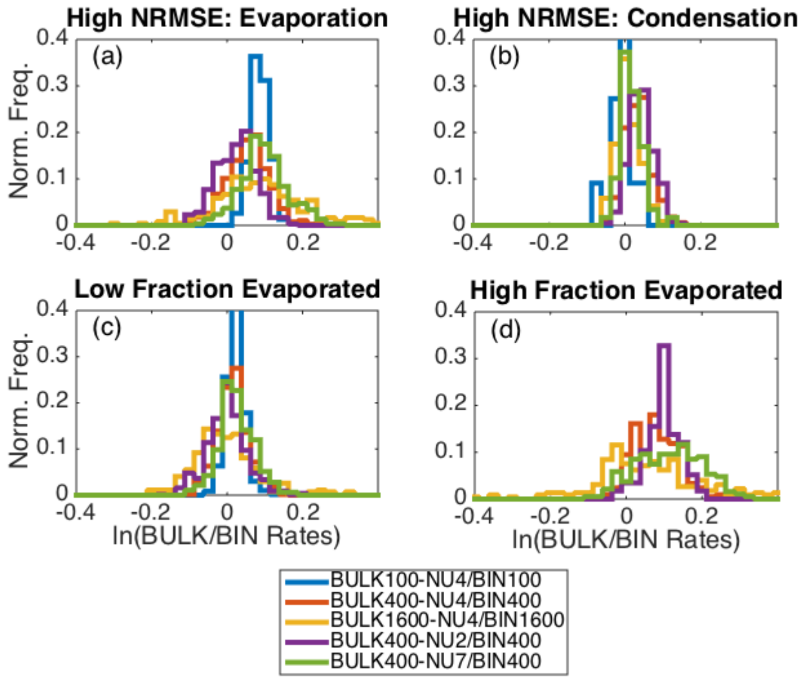

Figure 5. Similar to Figure 3. Histograms of the logarithm of the ratio of BULK to BIN condensation and evaporation rates but with conditional sampling of the data. (a-b) Only BIN simulation data points with an NRMSE greater than 0.6 are included in the analysis. (a) Shows evaporation and (b) shows condensation. (c) Only BIN and BULK simulation data points where the fraction of evaporated mass in one time step is less than 0.25 and (d) where the fraction of evaporated mass is greater than 0.25 are included in the analysis.

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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 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 BULK simulations the shape parameter is constant and has a value of 4. Therefore, specifically, the line is equal to (see the v dependency in Eq. 2).

In all three pairs of simulations, the mean shape parameter in the BIN 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 BULK prediction can be 50% higher than the BIN 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 BULK1600 and BIN1600 simulations cover a larger area of the S and $N\overline{D}$ 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). 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.

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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.

> 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.

Except when small residual supersaturation or subsaturation remains at the end of the

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