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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "A ubiquitous ice size bias in simulations of tropical deep convection" *by* McKenna W. Stanford et al.

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We thank the reviewer for their insightful comments. We feel they have helped make our study more robust and hope that any concerns have been alleviated in our provided response. Please note that any references to page or line numbers in our "changes to manuscript" responses refer to the final revised version of the manuscript and reference to any figure numbers in our "changes to manuscript" responses refer to revised figure numbers. Figures included for responses below are referenced as Fig. R1-R5. Note that although all 5 response figures (R1-R5) may not be referenced in this particular response, they are discussed in responses to reviews by both ACP referees. All 5 response figures are included in response to both anonymous referees for consistency of discussion. Figures added to supplemental material are referenced as Figures S1-

S4.

Major Points

1. Comment: A table showing the density and mass-size relationships of all hydrometeor species should be provided for FSBM. I would also suggest putting terminal velocity and mass relationships to all three tables. As mentioned in the manuscript, sedimentation process also causes the different behaviors of the overestimated hydrometeor size. Some related studies (terminal velocity impact on cloud and precipitation structure) should be cited too.

Response: Table 3 has been added to list the mass-size relationship parameters and terminal velocity-size relationship for FSBM. Terminal velocity-size relationship parameters have also been added for Thompson and Morrison in Tables 1 and 2. Note that the terminal velocity-size relationships given for FSBM in Table 3 are listed as ranges. This is because the v-D relationships used in the study come directly from ASCII files located in the /WRFV3/run/ directory of V3.6.1 of WRF. Figure R3 shows mass, density, and terminal velocity as a function of diameter in panels (a)-(c), respectively, using the ASCII file data for each of the 33 size bins of each hydrometeor species. Updated analytical formulas are not provided in the literature for the relationships shown in Figure R3, and therefore, v-D relationship as well as the rho-D relationship for snow are listed as ranges rather than a formula.

Changes to manuscript: In addition to the inclusion of Table 3 and the inclusion of v-D relationship parameters for the Morrison and Thompson schemes, we have added language on P16 L4-8 to indicate that v-D relationships may impact model size biases presented in this study, but that analyzing this possible contribution is beyond the scope of the study. Relevant references have also been cited that examine impacts of sedimentation on cloud and precipitation structure.

2. Comment: The upper limit of the Deq of hydrometeors in FSBM is less than 10 mm due to its relatively fewer bin numbers (33 vs. 36 from many other bin schemes). How

come the PSD, MSD and ZSD in Fig. 17 showing sizes reaching 10 mm for FSBM?

Response: The upper diameter limit for snow in the FSBM scheme within WRF is actually 19.877 mm (9.9387 mm radius). This can be found by looking in the WRFV3/run/ directory for V3.6.1 in the ASCII file named "bulkradii.asc_s_0_03_0_9", which lists the corresponding bulk radius bin for each FSBM species mass bin. Although these snow particles are extremely large, aggregates in reality achieve these sizes, and the density is assumed to be low (35 kg m-3).

3. Comment: Is the C-POL reflectivity data gridded? It will be tricky to show plan view just at 2.5 km of the C-POL reflectivity in Fig. 3(a) if the data is not gridded. What is the data sample size of the observed reflectivity for each level shown on Fig. 5? The unevenness of the sample size above and away from the radar can cause bias in the observed profile. How was the reflectivity calculated for each simulation? What wavelength was assumed in the model reflectivity calculation? Were mass-size relationships associated with particular schemes or the water equivalent diameter used to calculate the model reflectivity? How are the partially melted particles coated with water are treated in the calculation? Different ways of calculating the reflectivity will provide very different results. Some discussions about the uncertainties of the model reflectivity should be provided.

Response: Yes, the reflectivity data from C-POL is Cartesian gridded. Figure 5 has been revised according to Specific Comment #6 by Reviewer 1. We have provided sample sizes, normalized by domain area, of the data used in Figure 5 for each time period shown. While the C-POL domain is smaller than the WRF domains, the number of grid points $\geq$ 5 dBZ per kmˆ2 is comparable between C-POL and WRF for the 12Z-18Z time period, while the C-POL sample size per kmˆ2 is larger than WRF for the 18Z-00Z time period. Additionally, the larger sample sizes used by analyzing 6-hr time periods (rather than a single time step that was previously shown) suggests that sample size limitations would not erase the extremely large difference in reflectivity aloft shown in the 99th percentile profiles of Figure 5.

Reflectivity calculations assume Rayleigh scattering, which is valid for comparison with the (5.5-cm) C-POL wavelength in this environment. This calculation follows Smith (1984), is commonly used in studies, and is consistent with PSDs and single particle properties assumed in each of the schemes. Rayleigh reflectivity is now output by default for several microphysics schemes in WRF including the Thompson and Morrison schemes used here. As discussed in Smith (1984), the estimated Rayleigh reflectivity for ice could be slightly off, but any potential error is much smaller than the very large differences between observations and simulations shown in Figure 5. The equation does indeed account for the m-D relationship via the melted equivalent diameter calculation (Equation 5), and thus the reflectivity is diagnosed to change with changes in the m-D relationship.

Partially melted particles coated with water are not explicitly represented in the microphysics schemes. The peak in reflectivity near the melting level in the bulk schemes shown in Figure 5 is the result of a very simple parameterization in the WRF computed reflectivity, which is implemented to represent the "bright band" caused by water coated melting ice particles. This peak does not occur for FSBM since FSBM reflectivity is computed offline by summing reflectivity contributions from each hydrometeor size bin without implementation of the melting layer algorithm. Although the reflectivity peak caused by water coated melting ice could have significant errors, this does not impact our conclusions drawn for regions above this melting layer, which is the region we focus on.

Changes to manuscript: Importantly, we note that we have used an updated C-POL dataset provided by Alain Protat who has been added as a co-author. We have also gridded these C-POL radial sweep files ourselves to match the simulation horizontal grid spacing (1 km) and found a $\sim$2.5 dB increase, which is why the cross-section figures (Figures 3 and 4) change from the original version, however this increase is not central to any of our conclusions. We have included statements that C-POL data is Cartesian gridded and uses 1-km horizontal and 500-m vertical grid spacing in the manuscript on P9 L16-18. Figure 5 has been revised, as discussed in the response above and in Specific Comment #6 by Reviewer 1, and relevant discussion of Figure 5 has been revised on P10 L4-15 We have moved Equations 5-7 from Section 5.5 to the beginning of Section 5.1 (P9) to introduce the calculation of reflectivity when the subject is initially discussed.

We state that simulated reflectivity is calculated assuming Rayleigh scattering on P9 L14-15 and provide a brief explanation of why this is a good assumption.

Language has been added on P9 L9-13 to note the differences in reflectivity calculations between FSBM and bulk schemes and to note that the bulk schemes use a parameterization to treat reflectivity calculations of partially melted ice coated with water but FSBM does not.

4. Comment: Figure 4 is the same as Fig. 3 and Fig. 9 is the same as Fig. 8. It is hard to follow the discussions about these figures.

Changes to manuscript: The correct version of Figure 4 is now in place. The correct version of former Figure 9 is now represented in the bottom panel of Figure 7 (g-i), by which the old Figures 7-9 are now combined into a 3x3 panel that is the current Figure 7, as recommended in Specific Comment #2 by Reviewer 1.

5. Comment: It will be good to plot PSD of liquid and ice particles separately in Figs. 11 and 12.

Response: While separating these figures into liquid and ice is insightful from a model only perspective, we use the combined hydrometeor distributions because observations are not separated into liquid and ice species. Simulated liquid and ice MDs as a function of vertical velocity are shown in Figure R4 for T between -32 °C and -40 °C and Figure R5 for T between -8 °C and -16 °C, however they are difficult to interpret without the contribution of each species to the total mass for a given vertical velocity (e.g., liquid MDs can be very small, but not contribute much to the overall MDs if liquid

doesn't contribute much to the overall mass). This is the reason that we feel that it is better to draw inferences from Figures 11-14 in explaining some differences in (current) Figures 7-10. For example, Figure 14 shows that for temperatures between -8 °C and -16 °C, LWC can be significant in the bulk schemes for w > 5 m s-1 with corresponding very small MMDs, whereas LWC is insignificant in FSBM and MMDs are significantly larger. Snow and graupel MMDs in Figures 12-13 are large in all schemes for these temperatures, and therefore, it is known that cloud droplets must be causing the sharp decrease in 10% MD with increasing vertical velocity in bulk schemes in Figure 10.

6. Comment: The last sentence in the abstract is too strong. It is hard to imagine current microphysics schemes will uniformly produce a high bias in reflectivity.

Changes to Manuscript: Changed language on P1 L26-28 to indicate that this statement refers only to the microphysics schemes evaluated in the current study and not all microphysics schemes in general.

Minor Points

1. Comment: It will be good to also mention the lower size limit of the OAPs in page 4 line 15.

Changes to manuscript: Added lower limits of OAPs to P4 L16-17.

2. Comment: The threshold for simulated condensation mass mixing ratio is too small at 10-12 kg kg-1. Using this threshold may introduce grid points with unrealistic results. 10-6 kg kg-1 should be a good threshold for the analysis.

Changes to manuscript: All simulated and observed data now use a constraint of > 0.1 g m-3, which is the approximate TWC observational uncertainty at -40°C (see discussion in manuscript on P4 L29-33.

3. Comment: You probably referred to Fig. 6b in line 14 on page 12.

Changes to manuscript: Changed reference from Fig. 6c to Fig. 6b on P14 L6.

4. Comment: Page 1, line 16: using “different” microphysics. . .

Changes to manuscript: Changed “differing” to “different” on P1 L16.

Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-99, 2017.

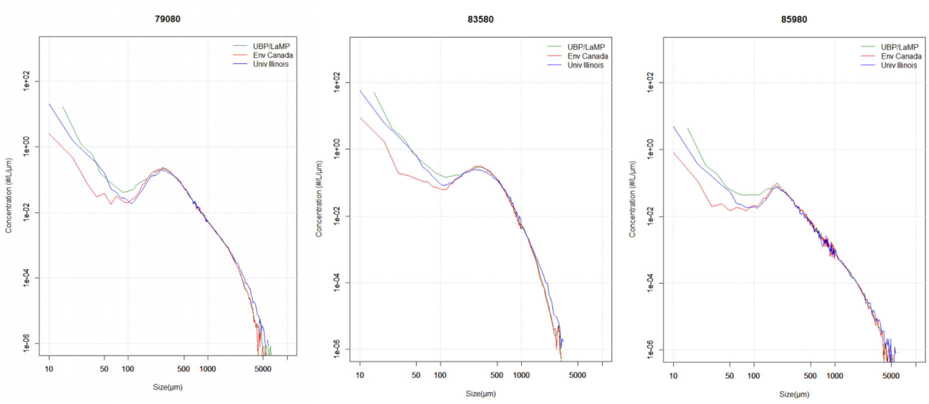

Fig. 1. PSDs from 3 different 1-minute composites (resulting from 5-second samples) showing PSDs derived from 3 different institutions. Number concentration is on the ordinate and diameter is on the abscissa.

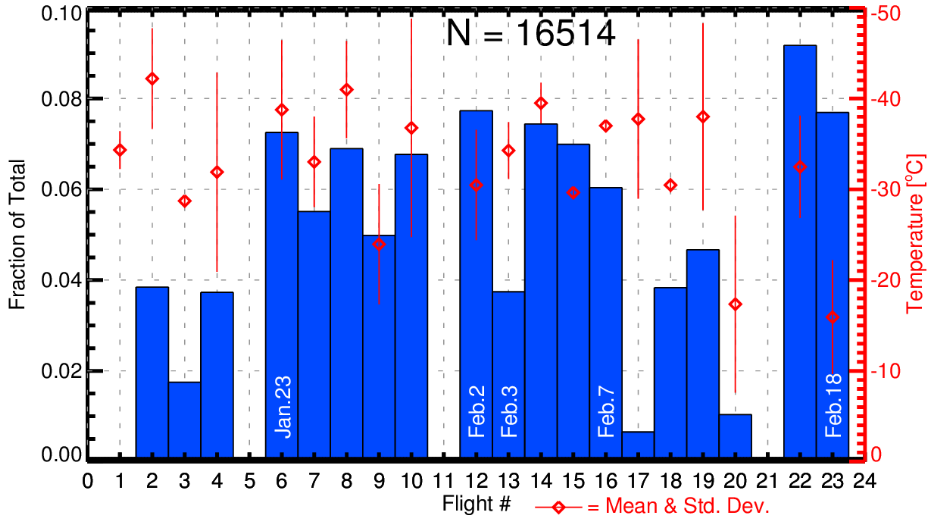

Fig. 2. Distribution of flight samples for the Darwin HAIC-HIWC campaign by flight number (blue bars). Red diamonds show the mean temperature for each flight, with lines that show +/- one standard deviation.

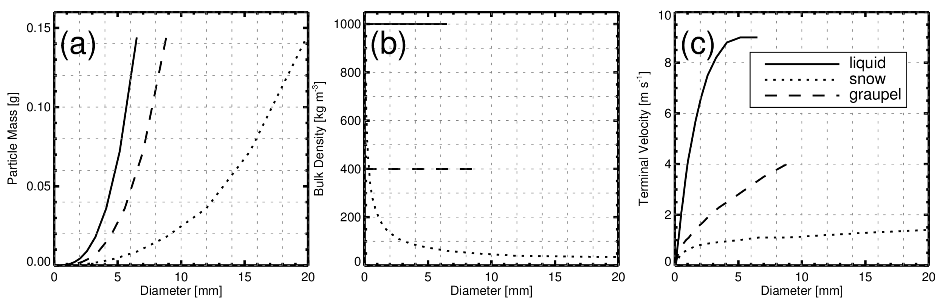

Fig. 3. FSBM (a) mass , (b) density, and (c) terminal velocity as functions of diameter for liquid (solid), snow (dotted), and graupel (dashed).

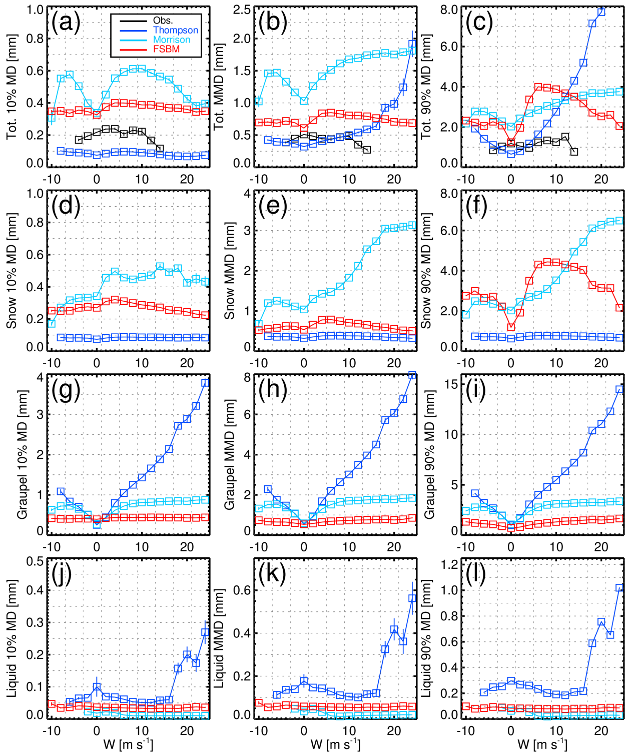

Fig. 4. (a)-(c) Combined hydrometeor 10% MD, MMD, and 90% MD, respectively, as a function of w for T between -32 °C and -40 °C. Snow MDs in (d)-(f), graupel MDs in (g)-(i), and liquid MDs in (j)-(l).

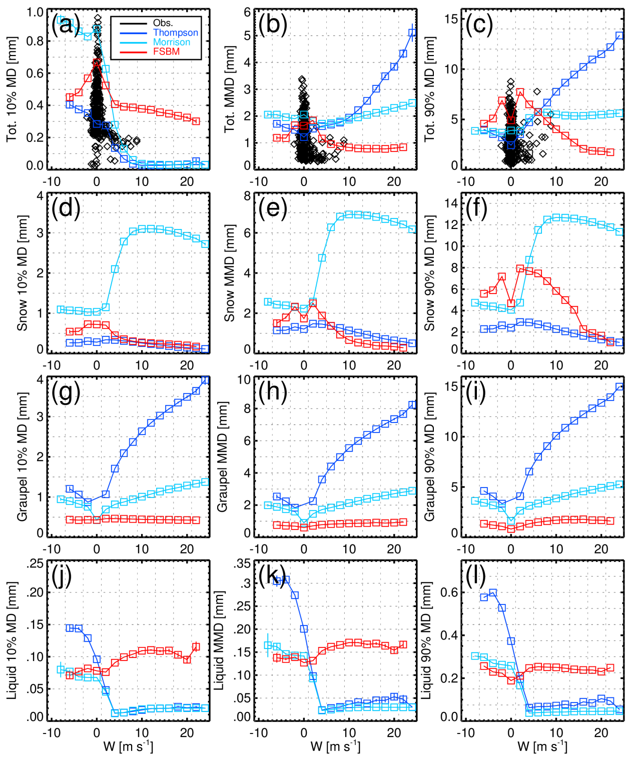

Fig. 5. As in Figure R4, but for a temperature range between -8 °C and -16 °C