

General comments. This paper uses polarimetric radar observations to test simulations using various microphysics schemes for summer convective cases over Germany. A major strength of the paper is the statistical evaluation over many cases in contrast to the approach often employed of focusing on a single case study. This topic is important as the representation of microphysics is a major source of uncertainty in NWP models. The paper is reasonably well written and the conclusions seem to be robust. My main concerns on the science center on 1) consistency between the radar forward simulator and internal assumptions and characteristics within the microphysics schemes, and 2) inconsistencies in the analysis of P3 (primarily for graupel/hail). These concerns are detailed in major comments below. I also include several minor comments, mainly to clarify certain issues or improve the presentation. Finally, a handful of technical/editorial comments are included at the end. Overall, I think the paper could be acceptable if the main comments are addressed.

Recommendation: *Major revision*

We would like to thank the reviewer for this review, which helped to improve the quality of our manuscript. Our point-by-point response is highlighted in blue below. The changes made to the manuscript are highlighted in red. A manuscript version in which all changes are highlighted is provided along with the revised manuscript.

Major comments.

1. One of my main comments concerns the consistency of assumptions and ice properties internal to the microphysics schemes with assumptions in the radar forward operator calculations using CR-SIM. It's mentioned a few times that these calculations are consistent, but in my view more detail is needed on this. For instance, what ice particle properties are needed or assumed by the forward operator calculations? I guess this includes particle density, size distribution information, and particle habit? Are there other inputs or assumptions made about ice particles in CR-SIM? I think it should be straightforward to couple the traditional bulk schemes (Thompson, Morrison) with CR-SIM. However, this seems less straightforward for coupling with SBM and particularly P3. In P3, the particle density (e.g., particle mass-size relation) varies across different regions of the size distribution. How was this accounted for? Particularly relevant for this paper, in all the schemes what is assumed for the distribution of liquid water on melting ice particles? This is particularly important in this paper given the focus on radar signatures of hail and particularly the reflectivity bias in all schemes in conditions of large hail (i.e., high reflectivities).

Perhaps these issues are discussed in some of the previous papers on CR-SIM, but more discussion is needed in this paper.

Many of the assumptions of the radar forward operator were discussed in Köcher et al. (2022) in their Section 2.4. The information about the CR-SIM forward operator comes mostly from their publication (Oue et al., 2020) and to a small extent from the study of their Fortran code (which is freely available on the Stonybrook University website: <https://you.stonybrook.edu/radar/research/radar-simulators/>). However, we are aware that the forward operator is very important for this topic. Therefore, we have extended the part about the forward operator in this paper and now directly provide more information about the assumptions of the forward operator, as well as the relevant citations for more details:

Section 2.1:

Key assumptions of CR-SIM include particle shapes and particle orientations: cloud droplets are assumed to be spherical, and raindrops and graupel are assumed to be oblate spheroids with aspect ratios that depend on droplet size according to Brandes et al. (2002) and Ryzhkov et al. (2011), respectively. Snow and cloud ice are assumed to be oblate with fixed aspect ratios of 0.6 and 0.2, respectively. P3 deviates from the traditional schemes regarding ice. Here, CR-SIM assumes that small ice and graupel are spherical, while unrimed and partially rimed ice is assumed to be oblate with an aspect ratio of 0.6. In terms of particle orientation, CR-SIM assumes that all particles are 2D Gaussian-distributed with zero mean canting angle according to Ryzhkov et al. (2011). The width of the angle distributions varies depending on the hydrometeor class: 10° for clouds, rain, and ice and 40° for snow, unrimed ice, partially rimed ice, and graupel. In terms of particle densities and particle size distributions, CR-SIM is consistent with the applied microphysics schemes. In most of the applied schemes, the particle density is constant and varies only between hydrometeor classes. Only the P3 scheme deviates from this, where the particle density of ice is not constant, but several mass-size relations are used. Following the P3 scheme, CR-SIM also uses multiple mass-size relations. In terms of particle size distributions, CR-SIM follows the same gamma distributions as the bulk microphysics schemes. The spectral bin scheme is a little more complicated. Here CR-SIM requires an additional input file containing the actual bins as simulated by the SBM scheme. There is no melting scheme applied by CR-SIM and as a result, radar signatures resulting from mixed-phased particles, such as for example a "bright band" (Austin and Bemis, 1950) cannot be simulated by the model. For more details and a discussion on the assumptions made by the radar forward operator CR-SIM, refer to (Köcher et al., 2022, Sect 2.4).

Regarding melting particles: The CR-SIM forward operator does not apply a melting scheme. Particles are either completely frozen, or completely melted, in accordance to the corresponding microphysics scheme. This of course means that the model will not be able to reproduce radar signatures produced by melting particles, which is not acknowledged so far. We added a part to the discussion acknowledging the fact that the absence of melting particles (especially melting hail) might add to the lack of simulated reflectivities above 50 dBZ:

Section 5.1:

(3) Melting particles: The microphysics schemes applied do not consider particles that are partially melted, all particles are either completely frozen or completely melted. The radar forward operator CR-SIM does not apply a melting scheme either. That means, it is not only impossible to reproduce certain radar signatures related to melting (e.g., a "bright band"), but also the increase in reflectivity due to partially melted hail particles cannot be simulated. The highest reflectivity events observed could be due to partially melted hail particles, which would translate to an increase in reflectivity that is not reproducible by the models applied in this study.

Section 6:

This might be related 1) to limitations due to resolution, 2) to density assumptions that are not representative for high density hail-like particles or 3) the absence of partially melted particles in the simulations.

2. Figure 5 and ~p. 16. I think the analysis here is a misinterpretation of graupel and rimed ice as simulated by P3. Graupel-like or even hail-like ice particles in P3 don't necessarily consist wholly of rimed ice mass, -- they may contain substantial mass grown by vapor deposition as well (but still have high particle densities expected for graupel/hail). Thus, I think it's incorrect to only include rimed mass for the mixing ratio threshold in Fig. 5 for P3. If the hydrometeor ID identifies a particular time/location as hail/graupel from the P3 output, I would include all ice (rime plus vapor grown) in the analysis. This is particularly relevant to the analysis of graupel/hail since there is no separate rimed ice category in P3. It seems quite likely that ice present at the 1 km level in P3 for summer convective cases will be fast falling and with a high rime fraction (and therefore hail-like) anyway.

Thank you for this comment. We indeed misunderstood graupel as it is simulated by P3. In their paper, Morrison and Milbrandt (2015) state that graupel is "filled in with rime", which we misinterpreted as consisting of only rimed mass. This is, as we understand now, not the meaning of this sentence. This is a very important comment, as it changes the graupel analysis regarding the P3 scheme. As suggested, we include now all ice in the P3 analysis. For a fair comparison, we expanded this to the other schemes as well and now include all ice classes for all schemes and the hydrometeor classification. Most of the corresponding figure (Fig. 5) did not change much, which we think confirms the statement that at 1 km altitude during our convective summer cases, most of the ice is graupel/hail-like anyways. However, some changes are visible, which means that there is also other ice present, even though the majority is made of graupel/hail. Noteworthy is probably the area of 'ice' events at 1 km height, based on mixing ratio (center right image of Figure 5, see the updated figure below). Relative to the other schemes, the P3 scheme now simulates less area of 'ice' events, which means that in the P3 scheme, the fraction of graupel/hail-like ice on the total ice in 1 km is a little higher than in the other schemes. However, our general interpretation of the results is not affected by this, because the area of 'graupel/hail' events in the P3 scheme based on mixing ratio was at the lower end of the schemes prior to these changes anyways. For a complete picture, we provide the hail/graupel figure (where really only hail/graupel classes are included, hence without the P3 scheme) in the supplement.

Please find the updated figure below (Note that we also adjusted the y-axis scale, to be consistent with the changes to the PSD-figure from comment 4).

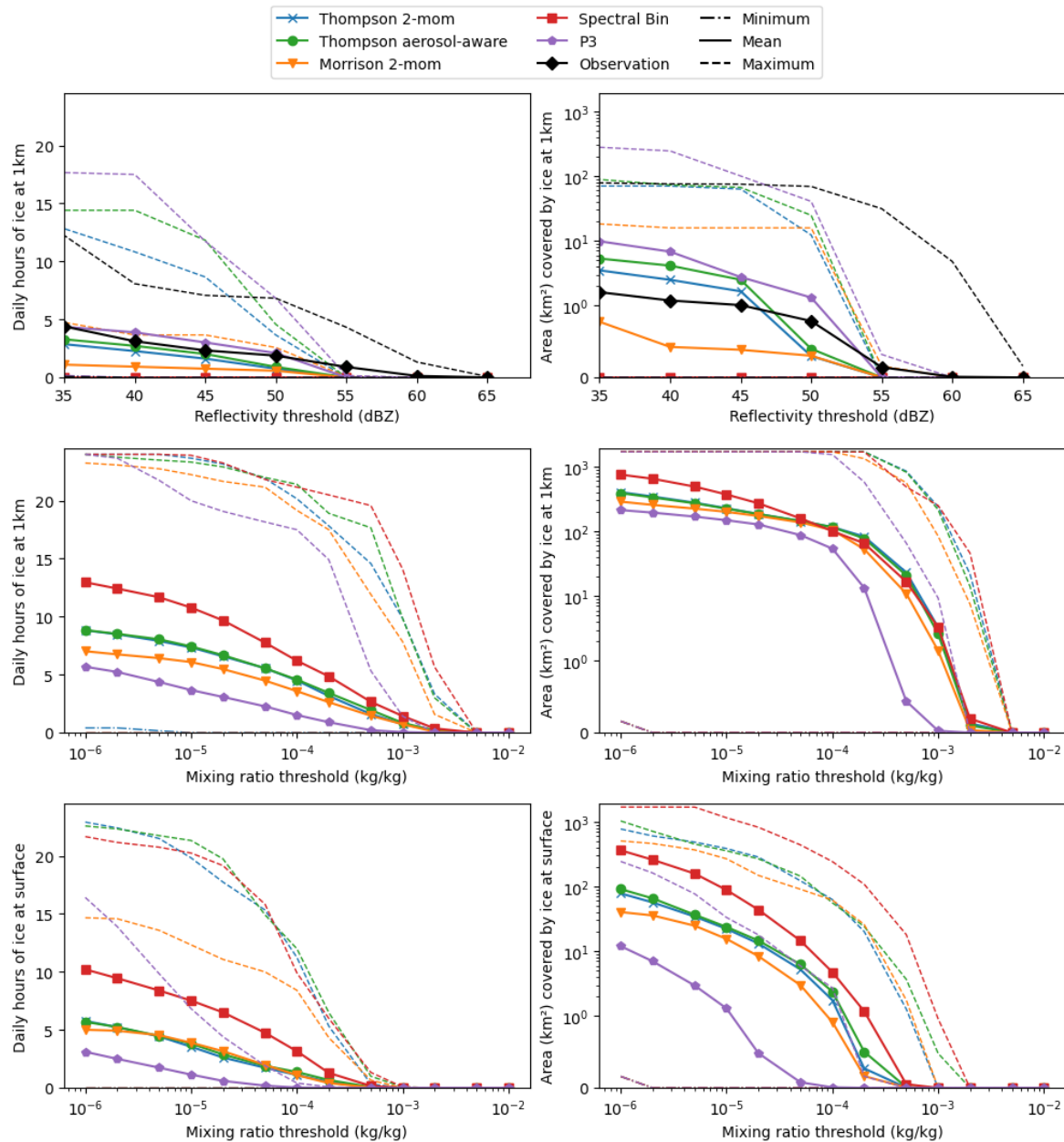


Figure 5: Same as Fig. 3, but for ice statistics. Frequency (left column) and area (right column) of ice events above various thresholds. Minimum (dashed-dotted line), mean (solid line), and maximum (dashed line) over the 30-day data set. First row: statistics based on simulated and observed reflectivity thresholds at 1 km altitude. Simulated reflectivity from WRF model output after applying the CR-SIM forward simulator (Oue et al., 2020). Second row: statistics based on mixing ratio thresholds at 1 km altitude. Third row: statistics based on thresholds for mixing ratio at the surface. The y-axis on the right side is logarithmically scaled, except for a small range around zero (0-1) with a linear scale.

In the paper, we changed the text at many instances in order to comply with the changes regarding the graupel/hail (now general ice) analysis. All instances of “graupel/hail” analysis have been renamed to “ice” analysis, except at instances where the conclusions really only concern graupel/hail. This concerns section 1, 2.2, 5 and 6.

Please refer to the marked up version that is provided along with this response for the details.

The wording in Section 5 has been changed more thoroughly. This concerns the following text passages:

Section 2.2:

Of all the ice classes, technically only the hail and graupel classes are of interest for high-impact weather. However, the microphysics schemes applied in this study do not provide exactly the same ice classes. For a fair comparison, we therefore include all ice classes into a common ice category. We assume that all these classes almost exclusively occur related to hail/graupel events during our summer time study period. Thus, vertical ice, wet snow, aggregates, ice crystals, high density graupel, low density graupel, hail, melting hail/big drops are combined and referred to as "ice".

Section 5:

The P3 scheme does not provide a hail or graupel class. Therefore, to allow for a fair comparison between the schemes, we included all ice into this analysis. Given that the dataset consists of convective cases mainly in summer, most of the ice present at 1 km altitude and below is graupel or hail-like anyways. For completeness, the analysis restricted to graupel and hail only (and thus without the P3 scheme) is provided in the supplement.

Section 5.2:

The middle row of Fig. 5 shows the same analysis as the top row, this time for the model's initial ice mixing ratios. A clear ranking can be seen between the microphysical schemes, both for area and for the frequency of ice events, which is almost independent of the mixing ratio threshold: the spectral bin simulations produced the most frequent and widespread ice events on average, while the P3 produced ice events that were the smallest and least frequent. The majority of the ice events at the height of 1 km are graupel events, because slower falling ice, like aggregates or cloud ice, is melting before it reaches the 1 km altitude.

3. I didn't see any discussion on the scale of the radar observations versus the model, other than discussion of 400 m grid spacing possibly explaining the low bias for the instances of high reflectivity associated with graupel/hail. Is there a general scale mismatch between the radar and the observations? Any scale mismatch is likely to be quite important for instances of heavy rain and hail. If the radar data is higher resolution, can it be appropriately averaged to give a comparable scale to the model data? Keep in mind that the effective resolution in models like WRF is about 5-7 times the grid spacing (Skamarock 2004, MWR).

The DWD radar data contain bins every 250 m along the range axis and every 1° along the azimuth axis. This corresponds to a distance between two azimuth radar bins of about 265 m at the nearer edge of the domain, about 685 m in the center of the domain, and about 1100 m at the far edge. The radar volume data is provided with 11 elevation angles

from 0.5° to 25° elevation, so there are less vertical levels in the radar compared to the model. The radar resolution changes with distance to the radar, which makes a scale analysis difficult. However, a radar also requires more than two samples to resolve an event, according to the Nyquist theorem. With a nominal grid sampling of about 700 m at the domain center, the effective resolution at the domain center is at a similar magnitude to the models effective resolution. However, we understand that this must be discussed, so we extended the data and method section with a part that states these numbers and the underlying assumptions on the resolution.

Section 2.1:

The horizontal model grid spacing is at 400 m. The DWD radar data is provided with bins every 250 m along the range axis and every 1° along the azimuth. The beamwidth is about 265 m at the closer domain edge, about 685 m at the domain center, and about 1100 m at the far edge. Simulated and measured radar signals are converted to a regular Cartesian grid with a grid spacing of 400 m using inverse range interpolation. This interpolation includes the four nearest data points, weighted by their distance $(1/\text{distance})^2$. Both, radar and model, require a sufficient spatial sampling to observe a physical phenomenon like a strong precipitation cell. Here, this translates into the question of an effective resolution, which is coarser than the nominal resolution. Skamarock (2004) estimates the effective resolution of WRF to be 5-7 times the nominal resolution, which would result in around 2 km effective model resolution in our case. Given that a radar with a nominal sampling of around 700 m (at the domain center) also needs at least 2-3 samples of a precipitation cell to begin resolving its true intensity, the "effective resolution" of such observations seems to be in a comparable range.

4. The SBM results from Figure 4 look rather strange, in particular, the sharp drop at diameters just above 4 mm. What is the explanation for this? Does it have something to do with how breakup is treated in this scheme? Or is this the maximum size of bins in the scheme?

The sharp drop means that no droplets larger than ~4 mm were simulated with the SBM scheme. The ~4-mm bin is the third highest bin, so in principle it should be possible to produce larger drops in the SBM simulations. However, the rain mass in the two largest bins is almost always 0 (or very close to 0) during our 30-d simulations. According to Shpund et al. (2019), a drop breakup scheme is applied that follows Kamra et al. (1991) and Srivastava (1971) and includes spontaneous breakup and collisional breakup. A snow breakup scheme is also applied, implying that raindrops formed from melting snow could be limited in size due to snow breakup. We believe it is possible that drop-breakup prevents the formation of the largest droplets. In any case, we believe that our current figure visually enhances the drop to 0 because of the logarithmic y-axis scale that never reaches 0. The large x-axis with raindrops up to 9 mm in size likely further enhances this impression. We therefore cut the x-axis at 6.6 mm (corresponding to the largest bin in the SBM model) and extended the y-axis to 0. This reveals that the simulated rain number concentration is 0 starting at the second largest bin (~5 mm).

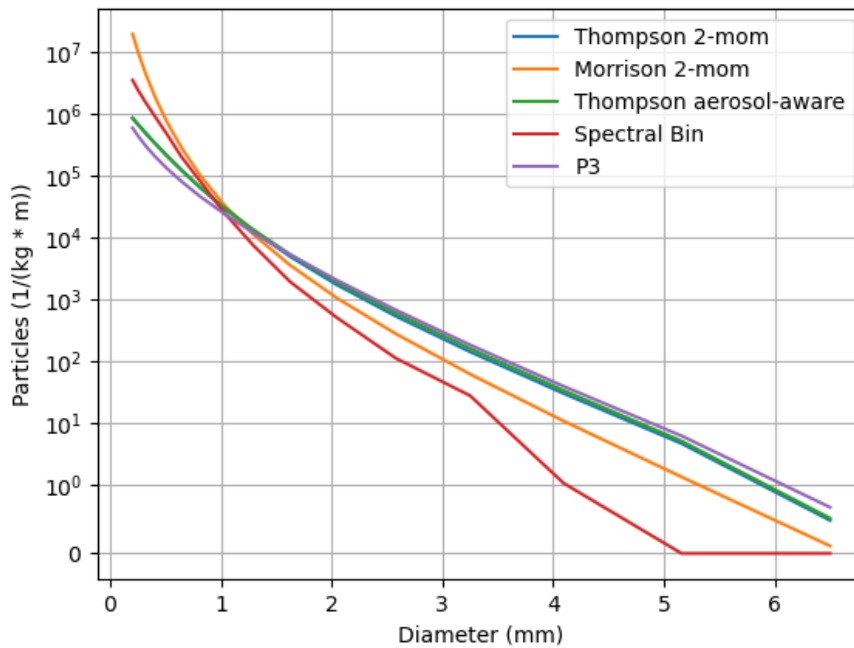


Figure 4: Mean rain drop size distribution over all 30 days at 1 km altitude. The y-axis is logarithmically scaled, except for a small range around zero (0-1) with a linear scale.

In the paper, we have added the relevant information about the break up schemes and the largest SBM bin:

Section 4.3:

The opposite is true for large raindrops greater than 4 mm, which were not simulated at all by the SBM scheme. In principle, the SBM can simulate larger raindrops, as the largest bin corresponds to raindrops of 6.6 mm diameter. According to Shpund et al. (2019), there is a drop break-up scheme applied that follows Kamra et al. (1991) and Srivastava (1971), which includes spontaneous breakup and collisional breakup. There is also a snow breakup scheme applied, which might limit the rain drop sizes for rain created from melting snow.

Minor comments.

Abstract, line 7. “heavy rain events” is imprecise. Can you state here the specific rain rates used to define such events?

The used rain rates are now specified:

All simulations, regardless of the microphysical scheme, predict heavy rain events (15, 25, and 40 mm per hour) that cover larger average areas than those observed by radar.

Line 26. I disagree that increasing resolution eliminates problems caused by inaccurate parameterizations, it addresses some of these problems. Thus, I suggest adding “some” before “inaccurate parameterizations”.

What we mean by that sentence is that an increase in resolution to the point that a process can explicitly calculated makes a parameterization unnecessary and hence removes any problem introduced by that parameterization. However, we understand that it is realistic only for some parameterizations to be removed by an increase in resolution. Therefore, we added the word “some” as suggested.

Line 32. Add “usually” before “predict”, since not all bulk schemes assume a predefined statistical function for the particle size or mass distributions (a few schemes predict processes directly from moments without assuming any functional form of the size distribution, e.g. Kogan and Belochitski 2012, JAS).

Changed as suggested.

Line 41. Not sure I agree that it is not known exactly which processes are poorly represented and I don't think the paper cited here (Morrison et al. 2020) makes this argument either – we have some idea of which processes are most uncertain or most poorly represented. Perhaps reword this sentence to “It is known that many processes, especially those involving ice microphysics, are poorly represented in numerical weather prediction models (Morrison et al., 2020).”

Changed as suggested.

Line 151. I'd add “single” before “case study”, as I think this states the point here better.

Changed as suggested.

Line 184. Not clear what you mean by “The missing information about the area of rain events is presented in the top right of Fig. 3.” What is missing? I think what you mean is simply “The area of rain events is presented in the top right of Fig. 3.”?

Changed as suggested.

Line 188. Confusing as written. Suggest removing “number of”.

Changed as suggested.

Line 240. Are the differences really “astounding”? Maybe “substantial” or “major” would be better?

Changed to “substantial”.

Lines 244-246. You might note that these relations of mass and reflectivity to diameter are true for liquid drops (or more generally, isometric particles).

Changed as suggested.

For (isometric) liquid drops, mass mixing ratio depends to the third power ($\propto D^3$) on particle diameter, while reflectivity depends to the sixth power ($\propto D^6$) on particle diameter.

Line 247. Technically, all of the bulk schemes here use complete size distributions, meaning they extend mathematically from 0 to infinity. Thus, it's better to just say “..few large particles may contribute significantly...” rather than “few or no large particles...”.

Changed as suggested.

Line 268. I think this could be reworded more clearly – I suggest replacing “due to the missing large raindrops” with “due to the lack of large raindrops”.

Changed as suggested.

Line 290. Technically droplet fall velocity and droplet size distribution are not processes. Suggest rewording this to “is affected by processes such as evaporation and drop sedimentation, ...”

Changed as suggested.

Line 300. They don’t evaporate faster because of high surface tension, it’s because evaporation in the schemes depends mainly on the number concentration times the mean radius (referred to as the integral radius), with some additional modification to account for ventilation.

Thank you for this correction. We removed this sentence completely, as we think the exact details of why small droplets evaporate faster should not be in the focus and distract from the actual point made.

Lines 315-316. This is not correct – the P3 scheme simulates not just number and mass mixing ratios of ice. By predicting additional ice attributes, it can distinguish between graupel-like and hail-like ice (for example, by differences in mean density, size, and fallspeed).

Thank you for this correction. In the context of the major comment 2, we include now all ice in the analysis, which is why this sentence was obsolete anyways and exchanged with the following two sentences:

The P3 scheme does not provide a hail or graupel class. Therefore, to allow for a fair comparison between the schemes, we included all ice into this analysis.

Lines 331-332. This is confusing. I’d reword to “a grid spacing less than about 250 m is required...”.

Changed as suggested.

Line 333. I’d add “when” before “further”.

Changed as suggested.

Line 339. Note that a multiple “free” category version of P3 exists (see Milbrandt and Morrison 2016, JAS). Thus, I’d reword this to “...this version of the P3 scheme uses only one ice class...”.

Changed as suggested.

Line 378. “likely” seems too strong of a word to use here. Perhaps reword to “which might be a resolution problem”. Same comment on line 415.

We included more possible reasons for the missing extreme reflectivities. The sentence reads now:

In summary, for the ice statistics, no model is able to reproduce the most extreme reflectivity statistics of greater than 55 dBZ, which might be a problem with density assumptions, the absence of partially melted particles in the simulations or a resolution issue.

Technical/editorial comments.

Line 4, abstract. Suggest adding “the” before “observation dataset”.
Changed as suggested.

Line 44. Perhaps replace “just this” with “such”.
Changed as suggested.

Line 78. Replace “are” with “were”.
Changed as suggested.

Line 84. Add “schemes” after “microphysics”?
Changed as suggested.

Line 99. The first “is” should be “are” (data here is plural).
Changed as suggested.

Line 179. I feel “then” could be removed.
Changed as suggested.

Line 226. Replace “it is relying on” with “it relies on”.
Changed as suggested.

Line 227. “mixing ratio” should be “mixing ratios”.
Changed as suggested.

Line 260. I think “github” should be “GitHub”?
Changed as suggested.

Line 260. Reword to “Because the bulk schemes do not actually have fixed size bins...”
Changed as suggested:

Because the bulk schemes do not actually have fixed size bins, the number concentration can be calculated for any droplet size.

Line 272. “simulate” should be “simulates”. Also “produce” should be “produces”. Same comment on the next line (line 273) as well.

Changed as suggested:

But given that the SBM scheme simulates high mixing ratio of rain mass, but at the same time produces too few heavy rain events based on the reflectivity produced, it stands to reason that this scheme generally produces too few large raindrops.

Line 278. “is” should be “was” and “note” should be “noted”.
Changed as suggested.

Line 279. “attribute” should be “attributed”.
Changed as suggested.

Lines 277-281. This sentence is very long, perhaps break it up into 2 sentences.

Split up to two sentences:

They noted that none of their simulations were able to successfully reproduce the observed polarimetric radar signatures. This is attributed to median raindrop sizes that are too large (Morrison and Thompson schemes) and a simulated frequency of very large raindrops lower than observed (Thompson scheme).

Lines 281-286. I'd suggest using past tense in the writing here, since you're describing what previous studies found.

Switched to past tense as suggested (changes in bold):

*In contrast, Putnam et al. (2016) **found** that both Morrison and Thompson 2-mom produce reflectivity values that are too high, which they **attributed** to PSDs containing too many large drops, too much precipitation coverage, and, in the case of the Morrison simulations, a bias due to wet graupel. With respect to our study, we can confirm too much precipitation coverage, and our results suggest that there are too many large raindrops in the Thompson simulations, which is consistent with Putnam et al. (2016) but in contrast to Wu et al. (2021). However, both studies **evaluated** the microphysical schemes using only case studies, which is not generally applicable to different weather situations.*

Line 297. Add a comma after "schemes". Also, replace "is getting smaller" with "becomes smaller".

Changed as suggested.

Line 298. "schemes" should be "scheme".

Changed as suggested.

Line 301. I think you can remove "also".

Changed as suggested.

Line 312. Add "are" before "of interest".

Changed as suggested.

Line 331. There's an extra right parenthesis after "(2015)".

Removed the extra parenthesis.

Line 332. Space is missing between "area" and "converge".

Added a space between "area" and "coverage".

Line 333. Remove "with".

Changed as suggested.

Line 335. I think "reflection" should be "reflectivity"?

Changed as suggested.

Line 338. I'd replace "from" with "with".

Changed as suggested.

Line 343. Replace "distribution" with "distributions".

Changed as suggested.

Line 374. Typo: “is” is repeated twice.

Removed one “is”.

Figure 3 caption. “Oue et al. (2020)” should be “(Oue et al., 2020)”. Same comment with the Figure 5 caption as well.

Changed as suggested.

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