Review: **Breakups are Complicated: An Efficient Representation of Collisional Breakup in the Superdroplet Method**

Emily De Jong et al.

The study presents development and preliminary results of drizzle/precipitation collisional breakup (CB) process in the framework of a particle-based ('superdroplet method', SDM) microphysical scheme. This process is physically essential to balance particle growth via collision-coalescence (CC). Including the CB process extends the CC implementation of Shima et al. (2009) in 'PySDM' code base.

The study presents results of an idealized monodispersed drop size distribution evolution under the combined effect of CC and CB, including sensitivity tests of conceptually simpler collisional breakup statistics. The results show that property-dependent CB can eventually balance the CC process which produces a near steady-state size distribution. The CB development was further tested in conjunction of other relevant warm-phase microphysical processes using a 1D rain-shaft setup, where it mainly shows CB is less important in shallow clouds.

The manuscript is reasonably well written and the interaction between various processes is mostly clear.

There is clearly a need for systematic development and documentation of the CB process for more accurate microphysical representation. This marks the importance and motivation of the study, and so the manuscript contributes to the open-source community of the particle-based microphysics. However, the study still shows very preliminary results which are not well justified in relevant cloud setup, and so it marks an incremental step on a path forward.

Based on the above and the specific comments below, I recommend acceptance with Major Revision.

Major comments:

- **Stochastic sampling of the fragment distribution.** Existing fragment size distribution parameterizations of Low and List (1982) and McFarquhar (2004) strongly suggest that each fragment regime (filament, disk, sheet) has underlying physics which is captured by the distinct size-modes in fragments distribution (McFarquhar (2004) section 2a).
  In this case, in Appendix B it's not clear how using a Cumulative Distribution Function as a function of size, rather than the fragments distribution themselves, you intend to capture well these potentially distinct and important modes.

- **Decision pathway, Figure 2 diagram** (L69-L75): To prevent defining a new superdrop size category, you eliminate completely the smaller superdrop (receiver), and so it is now treated as superdrop size category that holds all the 'satellite' unified droplet fragments - is this correct? [Figure 2, lower right arrow, lower/smaller superdrop].

If so, this is different from suggested by Low & List and applied by Seifert et al. (2005) and/or McFarquhar (2004), where the two remanent drops per breakup even are not eliminated.
Thinking about a deeper convective setup with sub-cm/cm -size drops in mind: your algorithm eliminates completely these huge (receiver) drop. These drops are quite low in concentration but should have significant effects over fields like drizzle/precip radar-reflectivity and differential-reflectivity. You should mark this as an assumption to be justified / preliminary results.

- **Abstract / Conclusion** (L310). The term 'rain suppression' is used in the abstract and conclusion (elsewhere) in a way it might be seen as one of the primary goals of the study. First, the term 'rain suppression' is mostly used in Atmospheric science to reflect increase in aerosol loading, followed by increase in cloud droplet number concentration. This has both microphysical (adjustments) and radiative implications.
Second, CB is an integral physical and mathematical part of the overall CC process, and thus it needs to be seen as an essential complementary process that delays precipitation growth due to CC.

  Both CC and CB clearly depend on physical properties of two interacting drops, hence the importance of the study is in determining realistically what are the relative roles of possibly opposing effects like large/small relative terminal velocity, collision efficiency, coalescence efficiency and characteristic fragments number and size at any such collisional even. The result (outcome) might than show: physically-based delay in growth rate of drizzle/precipitation -size particles a part of the CC process. At the limit of given 'enough' time for CC, the solution converges to near steady-state size distribution. This describes more reliably the presented results.

- **Abstract / Conclusion** (around L320) / **L260 / elsewhere**. The authors proposed the CB algorhytm "to be instrumental in further research on secondary ice production and mixed-phase processes". This is unnecessary and unjustified stretch.
  - First, the proposed CB algorithm/assumptions, being an integral development/part of the CC process, are not validated even for relatively simple warm-phase 1D ('rain-shaft') setup.
  - Second, referring to the Phillips et al. (2018) secondary ice production (SIP) suggested mechanism: the proposed SIP is primarily related to the process of supercooled drops freezing, during which part of the frozen shell fragments to produce ice-splinters (see the diagram in his Figure 7).
Moreover, since the probability for heterogenous freezing increase with drops volume, the freezing of 'satellite' (small) droplets fragments after collisional breakup are significantly less likely to happen in the relative warmer section of the mixed-phase region, for which the SIP mechanism is suggested
  - Third, the fragmentation discussed in this study results from different underlying physical mechanism compared to the freezing-drop fragmentation process (mode-

1, section 5 in his paper). The fragmentation resulted from collisions between frozen-drops (denser) and more fragile (less dense) ice particles like graupel/ ice/snow (mode-2), resulted primarily from the difference in terminal velocities. Hence, a dedicated microphysical model needs to predict simultaneously these degrees of freedom correctly as a function of modal size and density, which are far more complex than described in this manuscript

- Equation 6 (around L117): It is not clear how multiplicity, being equivalent to number concentration, can be equal to zero. I understand the sink term of the collision-coalescence can (potentially) deplete all the droplets within a superdrop category, where in that case it can be used as a criterion for sub-stepping. But then why you reinitialize the multiplicity with the one from the larger size superdrop category. Please explain.

<u>Minor comments:</u>

L62: The word ‘scaling’ here refers to computation efficiency. You have used this word for mathematical scaling as well. Please clarify.

L136: Why is that? Is this a choice for computational efficiency, or currently a specific limitation?
This suggest ‘PySDM’ cannot use collision kernels with turbulent enhancement effects reflecting real clouds, and hence cannot represent potentially important drizzle/precipitation acceleration processes. A specific feature of that acceleration is CC of comparable size drops at the vicinity of turbulent eddies.

Figure 3: The ‘units’ of ln(R) (natural log of the radius) doesn’t have physical units. It is sufficient to mention the spacing is in natural log. Please remove it.

L159: Please remove stochastic

L166: How can one see any manifestation of stochasticity in Figure 3, except for evolution of DSD with two distinct fragmentation distribution? We see different sampling strategies.

Figure 3: The remapping of the superdrop phase space to 128 size bins looks quite wiggly, and probably would need some attention once you compared to observed DSDs.

L177: Droplets with similar size has, by definition, similar terminal velocity. You might change to ‘comparable/close in size’.

L219: Please indicate where the microphysical processes algorithms come from (reference/s)?

L255-L260: Please include short discussion on the practical/minimal size range where Straub et al. (2010) can be considered relevant/active.

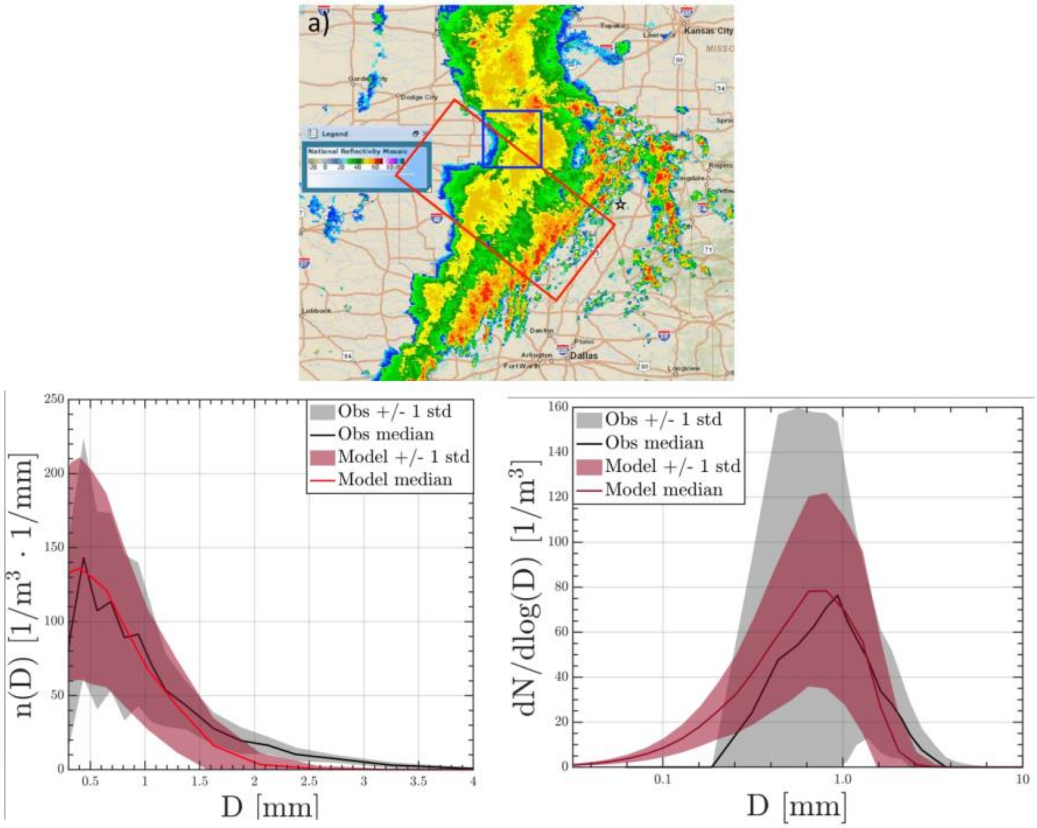
L258-L259 and elsewhere: It is written in multiple places (including pointing out to various references) that ‘Superdrop’ / SDM is ‘high-fidelity’ both in warm-phase and mixed-phase. In that case, except for scalability issues which are less relevant in case of 1-D/’rain-shaft’ or 2-D model setups, it’s not clear what are the challenges and complexity that prevents one from comparing development work to obs using idealized setup.
This is a minor comment given the manuscript clearly indicates this development work is preliminary incremental path forward subjected to validation.

Figure 7: The separate collision and coalescence panels are redundant, as we saw similar drizzle precip mass in Figure 6. Maybe a different colormap/scale will help. Moreover, for an overlapping single contour of rain and cloud, one cannot relate the rate to specific cloud/rain regime.

Last comment:

I’m relatively new to working with the SDM microphysics, but I have some experience with Seifert et al. (2005) collisional breakup parameterization implemented in a spectral bin microphysical scheme. The figure below depicts a fully-interactive 3D model with basic/medium -complexity mixed-phase microphysics, tested in an idealized 3D squall-line with 120-m/1-km vertical/horizontal resolution (idealize in the sense it simulates a section of a much larger midlatitude squall-line).
Comparing 100 random samples of surface precipitation size distribution from the stratiform area (in both model and obs), the results (yet to be published) shows reasonable realistic comparison.

I would be happy to see and experience comparable setups / results using any SDM code base.
Meanwhile, Shima et al. (2020) wrote wise words to manage our expectations and modesty:
“A more detailed evaluation of the model to explore the applicability of the new approach is an essential step forward. Our results strongly indicate that ice particle morphology can be predicted more accurately by further developing particle-based models. However, from this study, we cannot quantify the extent to which the refined representation of mixed phase cloud microphysics could improve the predictability of mixed-phase clouds’ macroscopic properties. Such proficiency can be addressed by conducting a thorough comparison with observations and other models”



References:

Bringi, V., Seifert, A., Wu, W., Thurai, M., Huang, G. J., & Siewert, C. (2020): Hurricane Dorian outer rain band observations and 1D particle model simulations: A case study. Atmosphere, 11(8), 879