Reviewer comments on the manuscript „A bin-microphysics parcel model investigation of secondary ice formation in an idealised shallow convective cloud" by R. James et al.

The secondary ice production (SIP) mechanisms receive exceedingly more attention in cloud research, as their importance in atmospheric ice formation becomes evident. There is, however, a strong disbalance between modelling efforts, field research, and laboratory experiments dedicated to the elucidation of SIP mechanisms, with the modelling studies clearly dominating the research landscape. Whereas in-situ aircraft-based research was recently gaining momentum thanks to new cloud particle imaging probes becoming available, the experimental efforts are scarce and are not yet capable of delivering physically meaningful and quantitative description of the SIP mechanisms so badly needed by cloud modelling community. Quite understandably, the SIP modelling scientists cannot wait for very slow advance of the state-of-the-art experimental activity and are therefore dependent on sieving the experimental data from past literature sources or venturing an extrapolation from recent but very preliminary experimental data.

The manuscript by R. James et al. reports on the modelling of various SIP mechanisms contributing to the enhancement of ice crystal number concentration (ICNC) in shallow convective clouds featuring cloud top temperature above -10°C. The main focus of the study lies in evaluation of the secondary ice formation upon collision between a rain droplet (diameter more than 150 µm) and an ice particle resulting in "splashing" of the droplet. In this mechanism, called "freezing fragmentation of droplets – mode 2" and subsequently referred to as "M2", the secondary water droplets produced in such a splashing event may contain fragments of ice crystals forming at the moment of droplet freezing initiation upon contact with ice. This mechanism was recently suggested on a basis of theoretical considerations in Phillips et al. (2018) and was not seriously considered being relevant for SIP, until the recent study of James et al. (2021) which produced some evidence of its potential importance. My comments are therefore mostly focused on the parametrization and implementation of this mechanism, because this is where my doubts are the strongest.

General comments.

A. According to (Phillips et al., 2018), the main criterium for M2 being active is the value of dimensionless energy DE that has to be higher than the critical value DE_{crit} (eqs. 7 to 9 of the manuscript). If this is the case, secondary droplets are produced upon collision of water droplet with solid ice surface (splashing condition). This criterium is accepted in the study as a basis for parametrization of secondary ice production rate according to M2 mechanism. (Phillips et al., 2018) derived this criterium analysing the results of droplet-droplet collision reported in (Low and List, 1982) and using the dimensionless collision energy formalism of (Testik et al., 2011), hinting at the absence of other laboratory data.

I seriously doubt that the critical value of DE obtained by applying the formalism of (Testik et al., 2011) to the droplet-droplet collision data can be immediately used for parameterizing splashing due to droplet-solid surface collision. Actually, this is also not the most straightforward approach as there is quite a number of studies describing splashing of droplets upon collision with curved solid surfaces. In many studies, a combination of dimensionless numbers (Weber, *We*, and Ohnesorge, *Oh*) is used to describe the onset of splashing when the critical collision velocity is reached for the droplet of given diameter. For example, (Charalampous and Hardalupas, 2017) have found that splashing of water droplets colliding with a larger spherical target is initiated for *We* larger than 400, whereas this value is around 120 for droplets colliding with the flat surface. Sykes et al. (2022) has used a more complex splashing parameter based on a combination of kinetic energy of collision, surface energy, and viscosity, but even there splashing does not occur for We less than 300. Sykes et al. (2022) also contains a nice overview of previous experimental results on droplet-surface collisions and is definitely worth discussing. Apparently, many factors influence the splashing behaviour upon collision, including roughness of the solid surface, amount of water adsorbed on the surface, and the curvature of the surface. And yet, none of these factors are included into the M2 parameterization of (Phillips et al., 2018).

It is straightforward to compare the critical Weber number with the DE_{crit} introduced by Phillips et al. (2018), because *DE* is just the so called modified Weber number (the ratio of kinetic energy of collision to the surface energy):

$$We = \frac{\rho_w \cdot D_{drop} \cdot v_{col}^2}{\gamma_l}, DE = \frac{\rho_w \cdot D_{drop} \cdot v_{col}^2}{12 \cdot \gamma_l} = \frac{We}{12}$$

Here I take for simplicity that the droplet is much smaller than the ice particle and therefore the mass term in equation (7) is just the mass of the droplet m_d. If the droplet and the ice particle are approximately of the same mass, then $DE = \frac{We}{24}$. From here one can easily define the relationship between the droplet size D_{drop} and the relative collision velocity v_{col} required to initiate splashing (see Figure 1 below). One immediately notices that according to splashing criteria based on $We > 120$ (collision with flat surface, the red dash line) the relative collision velocity for a given droplet size must be almost 10x higher than the velocity estimated from the condition of $DE_{crit} = 0.2$ (the blue dash-dot line). It is even worse if the condition of $We > 400$ must be satisfied to initiate splashing. The argument that the splashing was observed in the experiments reported by James et al. (2021) remains valid, because the collision conditions were indeed well above the splashing limit (the solid diamond data point at $D_{drop} = 5\ mm$ and $v_{col} = 5.3\ m/s$).

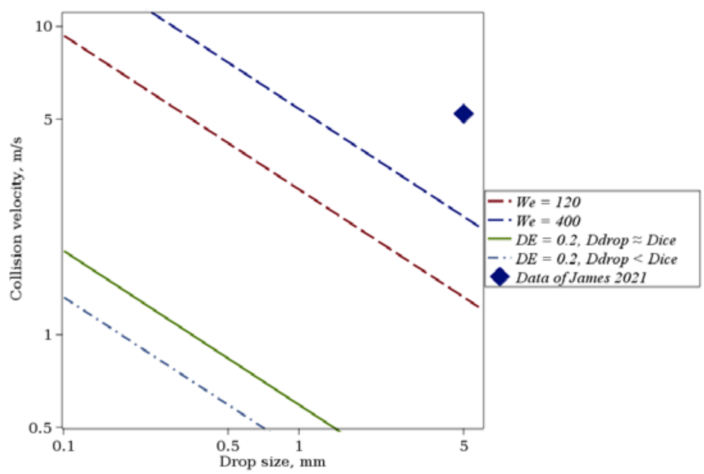

Figure 1. Splashing condition for droplet-solid surface collision.

So, the central question becomes, would the M2 mechanism contribute to any secondary ice production if the condition of $We > 120$ or even $We > 400$ has to be fulfilled to ensure splashing upon collision? Could you extend the sensitivity study into this range or is it rather pointless because neither droplets nor ice crystals grow to the sizes required to fulfil this condition?

B. Examination of the Figure 1 brings some follow-up questions. If the less restrictive condition of $DE_{crit} > 0.2$ can be used, what are the collision velocities that can be achieved assuming the free fall of droplets and ice crystals? Since the bin model handles the collisions explicitly and the significant enhancement of ICNC due to M2 is achieved, the collisions are obviously efficient in the model; however, it would be very useful to show the distribution of sedimentation velocities for droplets and ice particles as a function of cloud evolution. I would be especially interested to see the sedimentation velocities of ice particles with the aspect ratios and perhaps even effective densities predicted by the ice growth model. A comparison of the modelled sedimentation velocities for both ice particles and rain droplets with the values observed in the real shallow convective clouds would also be very instructive.

C. I was surprised to learn that apparently, this study is not the first attempt to include M2 into the cloud modelling. As mentioned in the Discussion section (lines 556 to 569) Zhao et al. (2021) and others have modelled the contribution of M2 mechanism using essentially the same parameterization provided by

(Phillips et al., 2018). However, no significant contribution to SIP has been demonstrated. So much is clear from the text of this manuscript but the detailed discussion of the possible reasons is missing. Given that the M2 is in the focus of this study, I feel that the manuscript would strongly benefit from such discussion.

D. On a side note, a few experimental studies of the freezing fragmentation of droplets (M1 mode) under more realistic conditions of free fall has been published after 2018 (Kleinheins et al., 2021; Keinert et al., 2020; Lauber et al., 2018). It might be worth checking the parameterization of (Phillips et al., 2018) aginst the data of these recent studies.

Summarizing, I find the presented study a useful exercise in modelling the SIP contributions to ice enhancement in a shallow convective cloud and as such well worth publishing. Not being a part of modelling world myself, I can only presume that the model framework itself is flawless and can handle the standard microphysics properly, given the validity of underlying parameterizations. In case of M2, I have strong doubts that the splashing condition is fulfilled in a shallow convective cloud and that the M2 SIP mechanism will be important under the circumstances. I do not doubt, however, that if the splashing condition were fulfilled, the M2 would become a valid SIP mechanism, but the validity of parameterization should be convincingly shown, through experiments or via small-scale physical modelling of a collision-freezing event. One possible suggestion would be to choose the modelling case differently (deep convective cloud?) to reproduce these conditions, but this would be a different study. I feel this is a major critical point since the study is dedicated to the evaluation of the M2 mechanism and therefore request “major revisions”.

Minor comments:

Line 73: Reference to (Hobbs and Rangno, 1990) is given twice.

Table 1: why is the effective density of *larger* colliding particle and the aspect ratio of the *smaller* colliding ice particle is given? Aren’t both parameters for both colliding particles are important to calculate the relative collision velocity?

Equation (9) should include $\max\,(DE - DE_{crit}, 0)$ as in (Phillips et al., 2018), to avoid getting negative values for subcritical dimensionless energy (if $DE < DE_{crit}$).

Line 156: *f(T)* is the mass FRACTION of water converted to ice after the end of the first freezing stage, not the “mass of frozen drop…”.

Figure 4: the line colours for Φ values of 0.3 and 0.1 should be swapped. The way it is shown, the lower value of Φ results in a stronger ice enhancement.

Supplement, figures S17 to S20: The colour bar on the right supposedly gives the number of particles per unit volume; the units of the number concentration are not given.

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