Review of 'Secondary Ice Production–No Evidence of Efficient Rime-Splintering Mechanism'

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On the surface this appears to be an excellent piece of work to revisit and quantify the rime-splinter (RS) mechanism of secondary ice formation using up-to-date laboratory methods. I am particularly impressed by the experimental design and set-up and the paper is well-written with few formatting issues.

The finding of the paper is that the is no evidence of an efficient RS mechanism and this is summarised in Table E1 of the manuscript. Most experiments in the paper show no evidence of secondary ice particles being produced, despite the amount of accreted rime being of the order of 0.1–1 mg rime. At $-5°$C this should have resulted in 10s–100s of secondary ice particles, but only in one experiment, at $-5°$C, were there ~ 20 ice particles produced.

Harris-Hobbs and Cooper [1] showed that the rates of SIP—from the trends in the early laboratory measurements of the RS mechanism—were consistent with observations to within a factor of ~ 3. Harris-Hobbs and Cooper developed a theory for explaining the dependence of the RS mechanism on the sizes of droplets. Mossop [2] found the production rate to depend on the presence of small ($d < 13\,\mu$m) as well as large ($d > 24\,\mu$m) droplets. This is parameterised by Harris-Hobbs and Cooper as follows:

$$P = Cf\left(T\right)\int_{D_0} g\left(L\right)\frac{\pi}{4}\left(L+D\right)^2 \times V_{impact} n\left(D\right)E\left(L,D\right)dD \tag{1}$$

where $L \cong 1$mm is the 'diameter' of the ice particle and D is the diameter of the drops, with:

$$g\left(L\right) = \frac{G_{<13}}{G_{all}} \tag{2}$$

and:

$$G_x = \int_0^x n\left(D\right)d^2 E\left(L,D\right)dD \tag{3}$$

$C = 0.16$ and $f\left(T\right)$ represents the temperature dependence of the RS mechanism. It is unity at $-5°$C and tapers linearly to zero at $-3°$ and $-8°$C. For the purpose of the calculations in this review I have assumed that $E = 1$, which is a likely maximum. This means that my calculations should overestimate the splinter production rate. As the size, $L = 1$mm, refers to a single ice particle in these experiments $g(L)$ is a constant for a given droplet size distribution.

Note that in the initial Harris-Hobbs and Cooper analysis Eq 1 was a double integral, but in this analysis there is only one ice particle—we do not need to integrate of the ice particle distribution.

Furthermore, the riming rate in this analysis is:

$$R = \int n(D) \frac{\pi (L+D)^2}{4} \frac{\pi \rho_w D^3}{6} E(L,D) \times v_{impact} dD \tag{4}$$

This is the integral of the product of the PSD, the area swept out per second and the mass of the colliding drop

Technical Issues

It is very useful that the authors provide the droplet size distribution in Figure 2 and Table 1. I encountered some issues when trying to interpret it.

1. Figure 2: firstly, for DSD3 there is no indication of the relative amount in each of the two modes. The smaller mode looks to be more numerous, but I think this should be reported in the paper.

2. Table 1: I am not sure what equation was used to fit the parameters D_g and σ_g. Is it the lognormal distribution in Eq. 5?

$$\frac{dN}{d\log D} = \frac{1}{D\sqrt{2\pi}\ln\sigma} \exp\left[-\frac{\ln^2(D/D_m)}{2\ln^2\sigma}\right] \tag{5}$$

   if this is the case then σ_g in your table should be unit-less as it is the standard deviation of $\ln\frac{D}{D_m}$.

3. Also in Figure B1 the units of the y-axis are listed as cm^{-3}, but you divided by N so I think it should also be unit-less.

Analysis of size distributions

I could not reproduce the size distributions in Figure 2 from the parameter fits in Table 1, so I decided to digitize the data using WebPlotDigitizer (`https://automeris.io/WebPlotDigitizer/`). This worked well and is shown in Figure 1.

I then tried fitting lognormal distributions to this data using the form in Eq 5. The result is shown in Figure 2. The fits approximately match the digitized data. The fit parameters are shown in Table I. As can be seen these parameters are a little bit different to yours, so I think it is worth showing the equation that was fitted to.

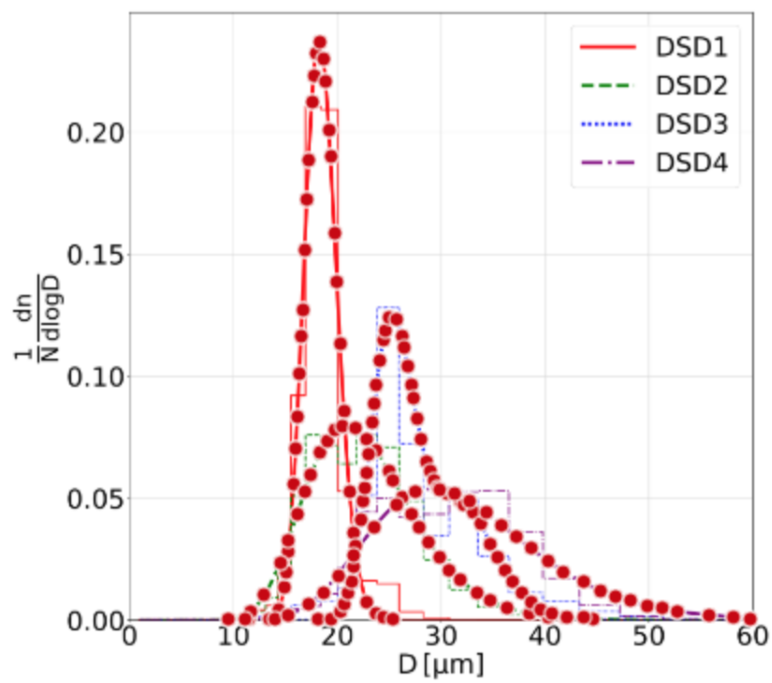

FIG. 1. Digitized data of the size distributions

TABLE I. Parameters of the size distributions from my analysis. Please note that values for N are arbitrary and do not affect the calculations when scaled by riming rate.

DSD	N	D_m (μm)	σ_g
DSD1	100	18.4	1.08
DSD2	100	20.8	1.28
DSD3			
mode 1	110	25.3	1.1
mode 2	40	32.1	1.1
DSD4	100	30	1.3

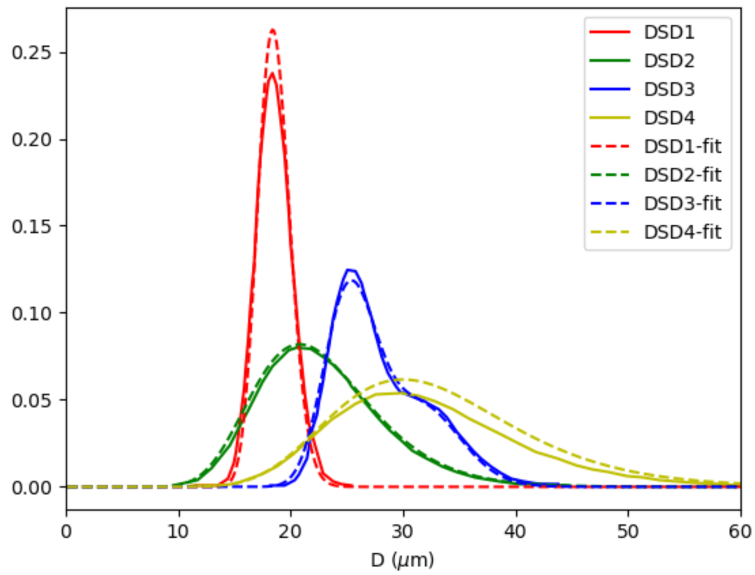

FIG. 2. My fits to the digitized data. Digitized data are solid lines and fit data are dashed lines.

Harris-Hobbs and Cooper Analysis for each DSD

I wrote a python script to calculate the SIP using the integral in Eq. 1 and the riming rate in Eq. 4 then I divided the SIP by the riming rate and divided by 1×10^6 to obtain the splinter production rate per milligram of rime accreted. The results, at $T = -5$°C, are shown in Table II. They show that the splinter production rates (2nd column of Table II) are very small for these drop size distributions, whereas if we assume all the drop sizes participate in RS the rates are much higher (3rd column of Table II). So while I am very supportive of the new set-up for studies of the RS mechanism, I think there is a major flaw in the paper to state that the measurements mean there is no evidence of the RS mechanism.

I have made the python script available to the authors, should they like to use the script I wrote. It is here `https://github.com/UoM-maul1609/dynamical-cloud-model/blob/master/pamm/python/hh_and_cooper.py`. You can alter lines 8-15 and run the script in the usual way. For the default case, the output is shown below. The important line is the last line, which is the production rate in number of splinters produced per mg of rime. To compute the rates for different size distributions alter the variable `nPSD` on line 14.

```
The integral of the PSD for n=0 is 6.2458575443444e-10
The G13 integrated over the PSD for n=0 is 1.3030461583782903e-14
The Gall integrated over the PSD for n=0 is 8.586451573231067e-09
Fraction of rime accreted of sizes less than 13 microns 1.517560714417395e-06
The riming rate integrated over the PSD for n=0 is 7.304337185264661e-16
Production rate per mg of rime 0.00040616010544473186
```

TABLE II. Parameters of the size distributions from my analysis.

DSD	Splinters produced per milligram of rime	setting $g(L) = 1$
DSD1	4.1×10^{-4}	71.3
DSD2	0.94	116.9
DSD3	5.59×10^{-12}	56.08
DSD4	3.0×10^{-3}	31.72

[1] R. L. Harris-Hobbs and W. A. Cooper, Field Evidence Supporting Quantitative Predictions of Secondary Ice Production Rates, Journal of the Atmospheric Sciences **44**, 1071 (1987).

[2] S. C. Mossop, Some Factors Governing Ice Particle Multiplication in Cumulus Clouds, Journal of the Atmospheric Sciences **35**, 2033 (1978).