Rapid ice aggregation process revealed through triple-wavelength Doppler spectra radar analysis

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General

This is a very well put together study, combining data from three co-located, vertically pointing radars to quantify aggregation efficiencies in the atmosphere.

It is the first attempt to retrieve the ice particle size distribution from multi-frequency Doppler spectra observations. It is satisfying to see that these results, in the main, corroborate our chamber observations.

The presentation is very good and there are no major issues. I recommend publication, but would like to see more information on the fall speed relations used and perhaps an assessment of how the results depend on mass-dimension relations.

As I have worked on similar problems before I wanted to see whether I could reproduce the findings from the information available in the paper, to check that my interpretation is consistent with the main findings in the paper. My reasons for doing this are to demonstrate how others may interpret your data, and to check that my interpretation is correct.

I present this alternate analysis, in a separate section below.

Specific Comments

Page 3, line 25 – sentence begins with “because”.

Page 7: Brown and Francis to convert between mass and size. The Brown and Francis (1995) relation is for ice crystals in cirrus clouds. There are more up to date mass-size relations that are published so I was curious if you have tried these, and whether a different assumption affects the results

Page 8: velocity power law – you don’t give examples of the fit parameters here, which makes it more difficult for others to understand your data. I wonder if you could give some example figures, or statistics of the fit parameters (the a and b coefficients).

Figure 4: convincing plot. Just a comment: I am surprised that the spectral reflectivity of the middle plot and bottom plot extends to just above 1.5 m/s , whereas the size distributions are much broader for the lower layer. Is this because the larger particles in the lower layer are less dense so that their fall speed saturates with increasing particle size?

Alternate Analysis

Validation: in order to better understand figure 4 I thought I would do a consistency check. I digitised your data from plots in figure 4 c, f, and i

First I wanted to calculate the mass flux, to see if this was roughly in-line with that expected and to see whether it was approximately conserved between levels. As you are aware the mass flux should be conserved in diffusional growth is not important.

I used the Brown and Francis (1995) relation to convert particle diameter to mass (as you have done)

$$m = 0.0185D^{1.9}$$

And, as you have not given the coefficients for the velocity-size relation, I have used a fall speed relation from Wang and Chang (1993):

$$v = 6.96D^{0.33}$$

My analysis is shown in Figure 1. I have calculated the mass flux at the top, middle, and bottom of the cloud presented in your figure 4. The values I have calculated are as follows

	top	middle	bottom
Mass flux 10^{-4} (kg m-2 s-1)	4.12	2.39	4.81

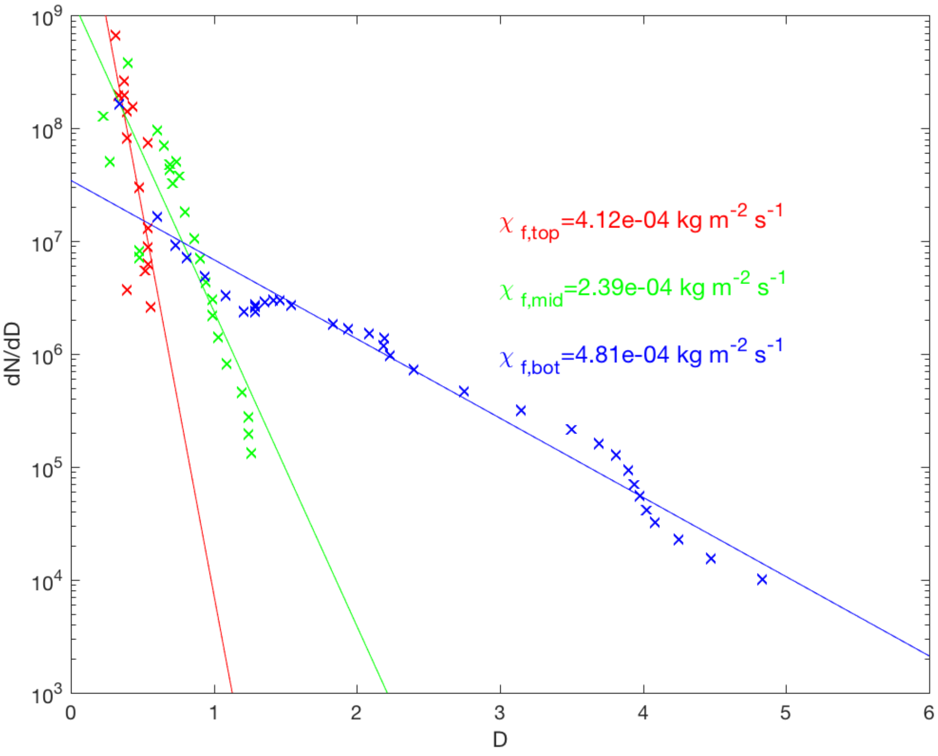

Figure 1. Analysis of your figure 4. Data points are taken from your figure 4, lines are exponential fits. Text shows the calculated mass flux. Colours are as follows: red (top of cloud); green (middle); blue (bottom of cloud).

We should expect that the mass flux increases if the particles grow by vapour diffusion, or decreases if the particles evaporate. If vapour diffusion is not important we should observe that the mass flux is conserved. Here we see approximately a factor of 1.7 reduction in the mass flux in the middle of the cloud. I suspect that these numbers are within the expected retrieval errors (or errors in mass-dimension / velocity – dimension relations, but it would be useful if you could comment on this.

The fact that I have used a velocity – dimension power law that is not based on your observation may also be responsible for this too: another reason why it would be helpful to see your velocity-size relations.

Next I thought I would try the analysis of Mitchell (1988) to attempt to calculate the aggregation efficiency. The relevant equation is equation 16 in Mitchell (1988).

$$\frac{d\lambda}{dz} = -\frac{\pi E_a I_1 \chi_f \lambda^{\beta+b-1}}{4\beta a\alpha\Gamma(\beta+b+1)\Gamma(2\beta+b+1)}$$

which can be rearranged for E_a, the aggregation efficiency. Here, β=1.9, b=0.33, a=6.96, α=0.0185 (SI units); λ is the slope of the size-distribution; χ_f is the mass flux (the mass falling through an area per second); Γ is the gamma function and I_1 is a definite integral to be calculated (see Ferrier et al 1994)

From the data in Figure 1 I was able to estimate $\frac{d\lambda}{dz}$ to be 7.9 (SI units); λ=6.42e3; and χ_f=2.39e-4 (SI units) are based on values in the middle of the cloud.

I calculated the integral, I_1, as 37.89 – code can be provided on request – feel free to contact me.

From these numbers, and rearranging Mitchell's equation above, one can estimate Ea to be equal to approximately 0.4.

This number is not too far from what you have used, but it would be useful to understand where the differences arise – I think your estimate is a little higher. For instance on page 12 you say you also use Mitchell (1988); hence, I wondered whether you could go through the calculation in more detail. I suspect this is due to the power laws used for velocity – size, but it may also be due to errors in fitting slope and intercept parameters to the data for instance.

I was not sure whether you had taken into account diffusional growth either. Taking into account diffusional growth with increase the slope, so the aggregation efficiency will need to be higher than I have calculated to lead to the observed reduction in the slope.

Additionally my estimate of Ea=0.4 assumes the mass flux in the middle of the cloud to be 2.4e-4, which is low compared to the top and bottom. If I use the higher mass flux 4.8e-4 (the value I calculated from your data at cloud base), in the calculation, the corresponding Ea is approximately 0.2.

In addition I thought I would try and reproduce a plot similar to your figure 5c. My Figure 2 shows these simulations using aggregation efficiencies of 1, 0.4 and 0.2. The finding here is that lower values of the aggregation efficiency yield lambda values closer to your observations at the 4 km level. Again I think the reason for this discrepancy may be because my calculations have used a terminal fall speed power law that does not match the observations for small crystals. Since the calculations appear to be quite sensitive to the terminal fall speed relation it would be really useful if you could present the measured fall speed (and regression coefficients) you have used.

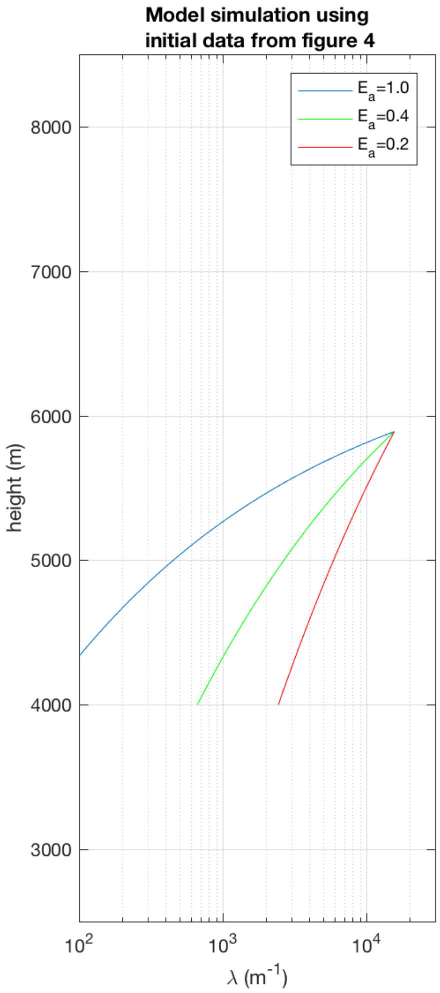

Figure 2. Model simulation using the initial conditions taken from the top of the cloud in figure 4, using different values of the aggregation coefficient.

Final word – I strongly support the statement about sizing particles down to 0.3mm, which would allow you to probe earlier stages of aggregation.

References

Brown, P R A, and P N Francis. 1995. “Improved Measurements of the Ice Water Content in Cirrus Using a Total-Water Probe” 12: 410–14.

Ferrier, B S. 1994. “A Double-Moment Multiple-Phase Four-Class Bulk Ice Scheme. Part I: Description” 51: 249–80.

Mitchell, D. 1988. “Evolution of Snow-Size Spectra in Cyclonic Storms. Part I: Snow Growth by Vapour Deposition and Aggregation” 45: 3431–51.

Wang, Chien, and Julius S. Chang. 1993. “A Three-Dimensional Numerical Model of Cloud Dynamics, Microphysics, and Chemistry: 1. Concepts and Formulation.” *Journal of Geophysical Research* 98 (D8): 14827. doi:10.1029/92JD01393.