GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L12810, doi:10.1029/2009GL038186, 2009

# Testing the influence of small crystals on ice size spectra using Doppler lidar observations

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Received 14 March 2009; revised 28 April 2009; accepted 4 June 2009; published 24 June 2009.

[1] Analysis of the vertical velocity of ice crystals observed with a 1.5$\mu$m Doppler lidar from a continuous sample of stratiform ice clouds over 17 months show that the distribution of Doppler velocity varies strongly with temperature, with mean velocities of 0.2ms$^{-1}$ at $-40$°C, increasing to 0.6ms$^{-1}$ at $-10$°C due to particle growth and broadening of the size spectrum. We examine the likely influence of crystals smaller than 60$\mu$m by forward modelling their effect on the area-weighted fall speed, and comparing the results to the lidar observations. The comparison strongly suggests that the concentration of small crystals in most clouds is much lower than measured in-situ by some cloud droplet probes. We argue that the discrepancy is likely due to shattering of large crystals on the probe inlet, and that numerous small particles should not be included in numerical weather and climate model parameterizations. **Citation:** Westbrook, C. D., and A. J. Illingworth (2009), Testing the influence of small crystals on ice size spectra using Doppler lidar observations, *Geophys. Res. Lett.*, *36*, L12810, doi:10.1029/2009GL038186.

## 1. Introduction

[2] There has been much controversy over the number of small sub-60$\mu$m particles in ice clouds. Measurements from forward-scattering cloud droplet probes suggest that these tiny particles are present in very large concentrations [e.g., *Boudala et al.*, 2002; *Platt et al.*, 1989; *Gayet et al.*, 2007; *Lawson et al.*, 2006; see also *Heymsfield and McFarquhar*, 2002], with important implications for the cloud's microphysical evolution, its interaction with radiation [*Boudala*, 2007; *De Leon and Haigh*, 2007], and remote sensing [*Donovan*, 2003]. On the other hand, there is evidence [*Gardiner and Hallett*, 1985; *Field et al.*, 2003; *McFarquhar et al.*, 2007; *Heymsfield*, 2007] which suggests that these small particles are in fact instrument artefacts, caused by large crystals shattering on the probe inlet, with the detector then sampling the numerous tiny fragments. General circulation models (GCMs) typically represent ice particle size spectra using a simple exponential or gamma distribution [e.g., *Mitchell*, 1991], with the concentration of particles of diameter D given by

$$N(D) = N_0 D^{\mu} \exp(-\lambda D) \tag{1}$$

The parameters $N_0$ and $\lambda$ are either diagnosed as a function of temperature T or deduced from the model ice water content (IWC), while the parameter $\mu$ is typically assumed to take a constant value (zero for a pure exponential). However, if the measured concentrations of small crystals are genuine, equation 1 substantially under-represents their numbers.

[3] To represent the small crystal observations, *Ivanova et al.* [2001] (hereinafter referred to as I01) have taken forward scattering spectrometer probe (FSSP) and 2D optical probe measurements from 17 flights through stratiform ice clouds, and used them to parameterize a two-mode size distribution for input into GCMs. In this scheme, large particles are represented by the simple gamma distribution described above, with $\lambda$ diagnosed from the cloud temperature T. However, a narrow bump centred at around 25$\mu$m is added to represent the small particles seen by the FSSP. Examples of these parameterized spectra at temperatures of $-15$, $-25$ and $-35$C are shown in Figure 1 for a fixed IWC of 0.01gm$^{-3}$. Number concentrations of crystals 25$\mu$m in diameter are typically 2–3 orders of magnitude higher than crystals 250$\mu$m in diameter at these temperatures, and will strongly influence the lower moments of the particle size distribution (e.g., optical extinction, deposition/evaporation rates). A similar representation was suggested for remote sensing studies by *Donovan* [2003].

[4] *Mitchell et al.* [2008] applied the bimodal parameterization above to a GCM and showed that these tiny, barely-falling crystals would have a significant effect on ice cloud coverage and radiative forcing, particularly in cold tropical clouds. It is therefore vital to determine whether these concentrations of small crystals are genuine or not, if simulation of ice cloud in numerical weather and climate models is to be realistic.

[5] *Westbrook* [2008] suggested that Doppler lidar measurements could be a sensitive test for the presence of genuine populations of small crystals, since the Doppler velocity would be significantly weighted by the small mode (which falls at only a few cms$^{-1}$). We test this idea using 17 months of continuous observations from the Doppler lidar based at the Chilbolton Observatory in Hampshire, UK, and compare the results to a forward model of the parameterized ice size, both with and without the controversial small mode.

## 2. Doppler Lidar Observations

[6] The measurements were made using a 1.5$\mu$m Doppler lidar (HALO Photonics Ltd, Malvern, UK). This instrument has a maximum range of 10km and measures profiles of backscatter and Doppler velocity every 32s, at 36m resolution, and operated continuously between September 2006 and January 2008 when the data presented here were collected. The lidar points directly at vertical: such a configuration is necessary to measure the fall speeds of

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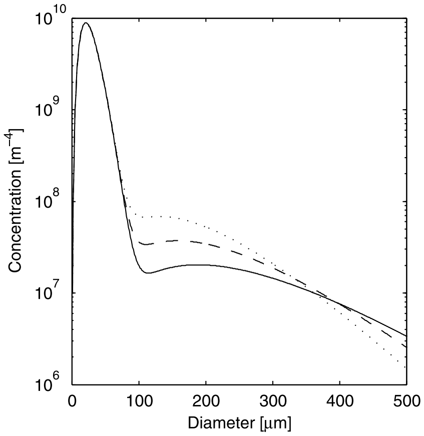

**Figure 1.** Example bimodal size spectra for T = −15 (solid line), −25 (dashed line), and −35C (dotted line). IWC is fixed at 0.01gm$^{-3}$.

the ice particles without contamination from the horizontal wind; however it can also lead to strong specular reflections from oriented planar crystals, which may bias the Doppler velocities. This is particularly a problem in mid-level, mixed-phase clouds (C. D. Westbrook et al., Doppler lidar measurements of oriented planar crystals falling from supercooled and glaciated cloud layers, submitted to *Quarterly Journal of the Royal Meteorological Society*, 2009). Comparison of the backscatter with a second lidar pointing slightly off vertical allows these regions of cloud to be identified and removed - see Westbrook et al. (submitted manuscript, 2009) for more detail. Liquid clouds, profiles with precipitation at the ground, and boundary layer aerosol are also removed using the same procedure described in that paper. This processing effectively limits our sample to stratiform ice clouds which are not raining/snowing at the ground, and our statistics should reflect the properties of these clouds. A total of 1.1 million 32s × 36m pixels were analysed: this breaks down into ≈85000 pixels per 2.5 C interval at −10C, decreasing to 22000 at −40C.

[7] For lidar measurements at non-absorbing wavelengths, an ice particle with a given shape and orientation is expected to produce a backscatter proportional to its projected area A, and the corresponding Doppler velocity would represent the area-weighted fall speed of the crystal population. However, at our 1.5$\mu$m wavelength there is some absorption as the light reflects around the inside of the crystal: as the particles become larger, this absorption increases, reducing the backscatter. This leads to the Doppler velocity being more strongly weighted towards the smaller particles than a simple area-weighting. We can write this as:

$$\langle v \rangle = \frac{\int N(D) A f(D) v dD}{\int N(D) A f(D) dD} + w \tag{2}$$

where w is the vertical wind speed, and the dimensionless factor f(D) falls off as a function of crystal size from f ≈ 1 for small crystals, to f ≈ 0 for very large ones. A backscattered ray of light with a 200$\mu$m path length through the ice crystal has f = 0.45 (Westbrook et al., submitted manuscript, 2009).

[8] Strictly, this analysis is only correct if the particle is much larger than the wavelength: for the small crystal mode this approximation may not be entirely correct. Mie calculations for ice spheres at 1.5$\mu$m (not shown for brevity) follow the predicted steady roll off in backscatter efficiency due to absorption for large particles. For very small spheres there is an increasing amount of oscillatory behaviour, leading to a slight enhancement in backscatter efficiency at 25$\mu$m (the peak of the small mode), and a suppressed efficiency at 15$\mu$m. In practice, for a cloud containing an ensemble of different ice particle shapes, any oscillatory structure will be smoothed out, and it seems unlikely that these departures from the simple geometric optics approximation will have a significant effect on $\langle v \rangle$, or on our conclusions below.

[9] Figure 2 shows the distribution of Doppler velocity for all the ice cloud sampled by the lidar over the 17 month period as a function of temperature (T is taken from the Met Office 12 km forecast model output over Chilbolton [see *Illingworth et al.*, 2007]. The distribution is broad, and has a clear trend with particles falling faster at warmer temperatures, indicating the influence of particle growth/aggregation. Note the sign convention of negative Doppler velocities for particles falling toward the lidar.

[10] Smoothing the lidar data over 10 minute periods before calculating the statistics leads to a narrower distribution as shown in Figure 2 (right), removing small scale variations in w, although some influence from lower frequency waves may still be present in the distribution. Since we are looking at stratiform clouds we expect that large scale ascents will be weak. *Westbrook* [2008] estimated that the maximum fall speed for a compact 60$\mu$m ice particle is 0.07ms$^{-1}$, so given the observed velocity data we conclude that the small crystal mode does not completely dominate the lidar signal in most clouds; however it could have a less extreme influence. We investigate this by comparing the observed mean values to the forward modelled area-weighted velocities from I01's bimodal size spectra.

## 3. Comparison With Ice Parameterizations

### 3.1. Including Small Crystals

[11] The mean Doppler velocity for all ice clouds sampled as a function of temperature from the distribution above is plotted in Figure 3. The temperature trend is marked, with velocities increasing from ≈0.2ms$^{-1}$ at −40C to 0.6ms$^{-1}$ at −10C. For this average over 17 months we expect any residual influence of w in the average values to be positive and very small compared to the total observed velocities in Figure 3.

[12] Ice particle size spectra were calculated as a function of temperature as described by I01, superimposing two gamma distributions:

$$N(D) = N_{0s} D^{\mu_s} \exp(-\lambda_s D) + N_{0l} D^{\mu_l} \exp(-\lambda_l D) \tag{3}$$

For the large particles $\mu_l$ = 2.64 and $\lambda_l$ is diagnosed from T using fits to the aircraft data. For the small mode, $\mu_s$ = 3.24 and $\lambda_s$ is fixed at 3.65 × 10$^4$ m$^{-1}$ (giving a mode centred at

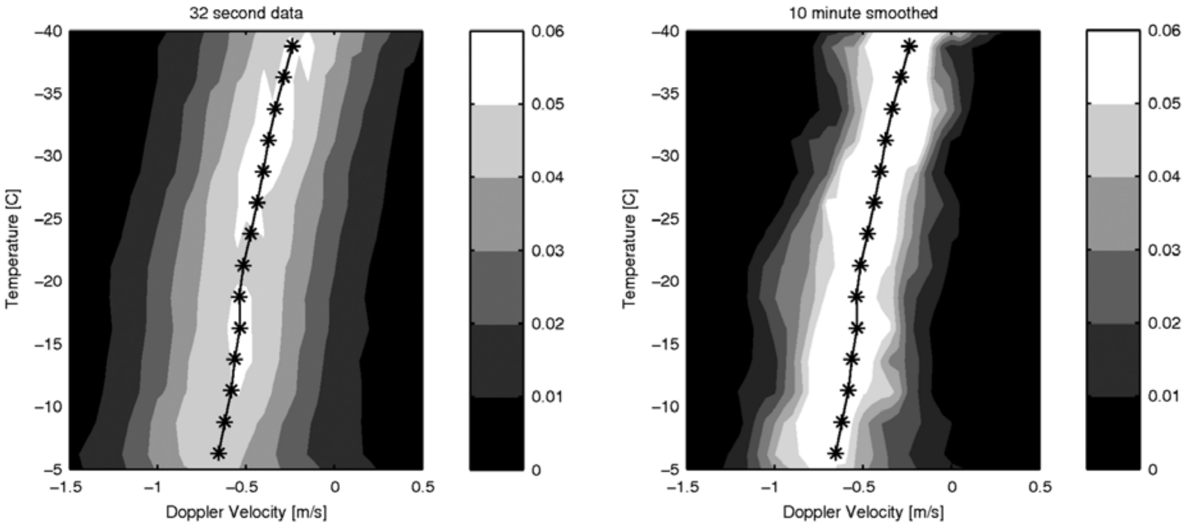

**Figure 2.** Filled contour plot showing distribution of lidar Doppler velocity. (left) Distribution of raw 32-s data; (right) same when 10 minute smoothing is applied. Gray scale indicates frequency in a particular velocity and temperature bin; frequencies are normalised such that the total in each temperature bin = 1. Bins are 0.05ms$^{-1}$ × 2.5C. Line shows mean velocity.

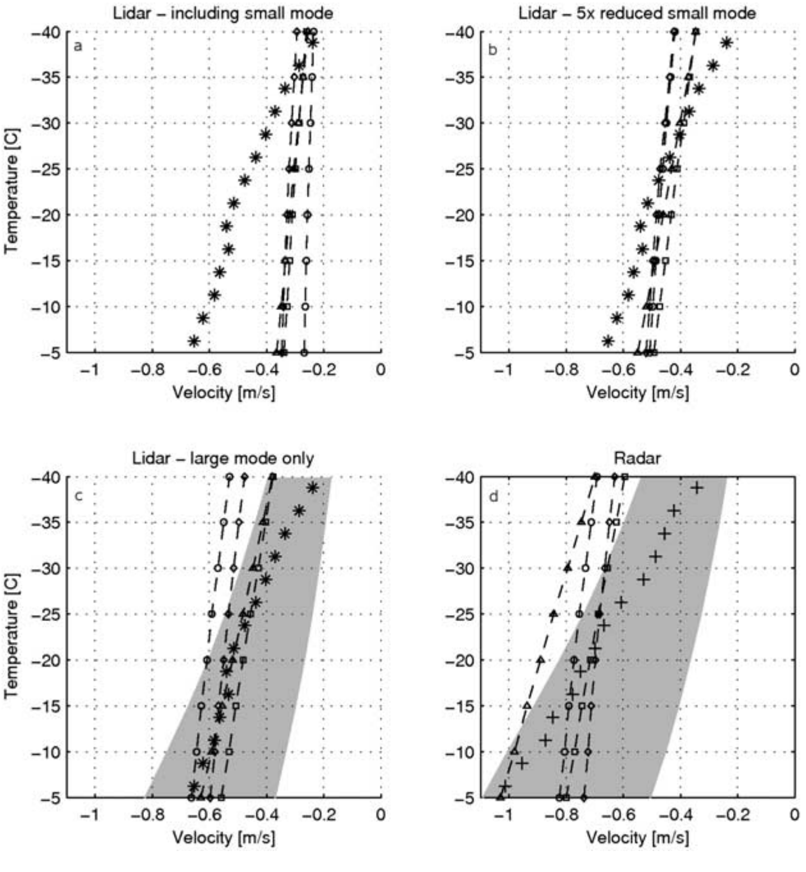

**Figure 3.** Average lidar Doppler velocity as a function of temperature (stars) compared to forward modelled area-weighted velocity when (a) small crystals are included, (b) when the small mode is reduced by a factor of 5, (c) when only the large mode is included. (d) Doppler velocity measured by 35GHz radar (crosses), compared to forward modelled m$^2$-weighted fall speeds. Symbols indicate different assumed m-A-D relationships: square = planar polycrystals, triangle = rosettes, diamond = aggregates, circle = cold-type. Gray shaded region in Figures 3c and 3d shows range of velocities predicted by *Wilson and Ballard*'s [1999] parameterization for IWC = 0.001–0.1gm$^{-3}$.

**Table 1.** Mass-Area-Diameter Relationships Used in This Study

| Particle Type: | Mass-Area-Diameter Relationship [cgs]: |
|---|---|
| Planar polycrystals | $m = 0.04953D^{2.852}$ $A = 0.2285D^{1.88}$ |
| Bullet rosettes | $m = 0.0026D^{2.75}$ $A = 0.2839D^{1.889}$ |
| Aggregates | $m = 0.0028D^{2.1}$ $A = 0.2285D^{1.88}$ |
| Cold-type particles | $m = 0.003D^{1.9}$ $A = 0.17D^{1.62}$ |

approximately 25$\mu$m). There is a simple partitioning of IWC between the two modes: this depends weakly on $\lambda_l$, and was inferred from aircraft data. For the range of temperatures sampled here, the fraction of the total IWC contained in the small mode was essentially constant at 11%. This percentage fixes $N_{0s}/N_{0l}$, and the concentration of small crystals relative to the large mode. The spectra in Figure 1 are examples of this prescription. Crystals smaller than 100$\mu$m compose 35–42% of the total projected area of the cloud in this scenario, depending on the temperature.

[13] These size spectra were then used with the mass- and area-diameter relationships of I01 to calculate the area-weighted fall speed of the crystals using *Mitchell*'s [1996] formula. Although *Westbrook* [2008] shows that *Mitchell*'s [1996] method can overestimate the velocity of sub-100$\mu$m particles, the absolute error is of order 0.02ms$^{-1}$ and is small relative to the overall forward modelled velocities (which are influenced by both modes). Air densities were assumed for each temperature based on a standard mid-latitude atmosphere [*International Organization for Standardization*, 1975]. Because $\lambda$ (rather than $N_0$) is diagnosed from T, the forward modelled velocity for a given temperature does not depend on IWC.

[14] The forward modelled velocity is plotted as a function of temperature in Figure 3a: given the analysis in section 2 we expect this to be somewhat faster than the measured lidar velocities due to the absorption effect at 1.5$\mu$m. However for temperatures warmer than $-35$C we find the opposite trend: forward modelled velocities are slower than the observations, by almost a factor of two at warm temperatures. We also note that the forward modelled curve is essentially independent of temperature at $\approx$0.3ms$^{-1}$. These discrepancies both suggest the small crystal mode is having too strong an influence on the area-weighted velocity.

[15] One concern about this conclusion is that it may hinge on the assumption of a particular set of (perhaps unrepresentative) mass- and area-diameter relationships. I01 assumed the large mode to be planar polycrystals; we have recalculated the forward modelled velocities using relationships for bullet rosettes (I01), aggregates [*Mitchell*, 1996], and 'cold-type' particles (m-D relationship [from *Brown and Francis*, 1995], A-m relationship [from *Francis et al.*, 1998]): see Table 1. For rosettes we follow I01 who used a slightly altered partitioning of IWC between small and large modes; for the other habits we assume the same partitioning as for planar polycrystals.

[16] For rosettes and aggregates the forward modelled velocities are very similar to the planar-polycrystal curve. For cold-type particles the modelled velocities are even slower, re-enforcing our conclusion that there are too many small crystals. Since analysis of aircraft images [*Korolev et al.*, 2000] indicate that most ice particles in stratiform clouds are irregular polycrystals or aggregates these four curves should give a good idea of the sensitivity to realistic changes in particle shape, and so we can be confident that the inconsistency of the forward model with the observations is due to the representation of the particle size spectrum, and not the particle shape.

[17] A second concern is that I01's large mode might not contain enough big, fast falling particles, biasing the forward modelled velocities too low. To test this, Figure 3d shows coincident Doppler radar measurements from ice cloud observed by the lidar, for a continuous 6 months subset of the total 17 month period. Since the radar is only sensitive to the large mode, we have plotted the average radar Doppler velocity as a function of temperature, and also forward modelled the reflectivity-weighted fall speed from I01. The comparison is encouraging – at warm temperatures the measured velocities are within the spread of uncertainty from the different m-A-D relationships. At cold temperatures the radar velocities are appreciably lower than the forward modelled values, indicating that if anything I01's large mode contains too many fast-falling crystals in the large mode, rather than too few. Given this evidence, we are confident that our conclusion that there are too many small crystals is robust.

## 3.2. Reduced Small Mode

[18] We have also forward modelled the size spectra with the small mode reduced by a factor of 5 ($N_{0s}$ reduced fivefold). This would correspond to sub-100$\mu$m crystals composing only 11–13% of the total projected area, assuming planar polycrystals. The resulting velocities are shown in Figure 3b, and are now much closer to the observations, although they are still $\approx$0.1ms$^{-1}$ too slow for clouds warmer than $-25$C. The much smaller contribution to the total projected area (and therefore area-weighted velocity) from the small crystals in this scenario means that we are unable to rule out this reduced small mode, given the other uncertainties involved in the comparison.

## 3.3. Large Mode Only

[19] Figure 3c shows results of forward modelling I01's size spectra if only the large mode is included. Sub-100$\mu$m crystals make up <1% of the total area in this scenario. The modelled velocities are faster, and at warm temperatures are close to the lidar observations, while falling somewhat faster than the lidar velocity at cold temperatures. This is consistent with the radar observations, suggesting that the number of fast-falling particles in the large mode is overestimated in I01's large mode relative to our sample.

[20] For comparison, we have also forward modelled the parameterization of *Wilson and Ballard* [1999]. In this scheme a simple exponential size distribution (equation (1) with $\mu = 0$) is assumed, with $N_0$ diagnosed from temperature, and $\lambda$ deduced from the model IWC. Mass- and velocity-diameter relationships are defined by *Wilson and Ballard* [1999], and we apply the A(D) relationship for aggregates from *Mitchell* [1996] to calculate the area-weighting. The shaded region in Figure 3c shows the range of velocities predicted for IWCs between 0.001–0.1gm$^{-3}$, consistent with the lidar observations. Forward modelling of the radar is shown in Figure 3d: again this is consistent with the observations. The temperature trend appears realistic,

especially given higher IWCs are correlated with warmer temperatures.

## 4. Discussion

[21] Doppler lidar observations have been used to infer whether measurements of high concentrations of small crystals in ice clouds are likely to be genuine or not. The Doppler velocity distributions show a systematic increase in velocity with temperature as the size distribution becomes broader. Forward modelling of the area-weighted velocity from bimodal size-spectra is inconsistent with the lidar observations, and strongly suggests that the large numbers of small particles measured by in-situ are instrument artefacts in many cases. Forward modelling with the large mode only gave results which were the most consistent with our observations. An intermediate case with a fivefold reduced small mode could not be ruled out, but even in this case the area of the small crystals (along with any associated radiative effects) is substantially reduced (by a factor of 3).

[22] We do not wish to polarise the issue: clearly in a number of situations small ice particles *are* present, especially near cloud top where there may well be recently nucleated particles present, and crystals in the early stages of growth. It would also be valuable to make similar measurements in cold tropical clouds where high concentrations of crystals might be nucleated. However, we conclude that the measurements of numerous small particles at *all heights* in mid-latitude ice cloud are inconsistent with our lidar observations, which are of course unaffected by shattering, and should not be included in numerical weather and climate model parameterizations.

[23] One limitation of this study is that the lidar is unable to penetrate optically thick cloud: this means that in deep systems, only the lowest 2km or so will be observed. This implies that at cold temperatures the sample is biased towards thinner clouds producing less ice (which the lidar can see through), and presumably lower velocities. So the 'true' $\langle v \rangle$ at cold temperatures may be even faster than in Figure 3 and this would re-enforce our conclusion about the small crystal mode. Another limitation is that 25% of the cloud sampled was rejected because of specular reflection from oriented planar crystals, which might bias the sample; on the other hand, coincident radar reflectivity (Z) measurements show a similar distribution for both specular and nonspecular cloud (Westbrook et al., submitted manuscript, 2009).

[24] Future work will focus on calculation of f(D) using ray-tracing simulations of polycrystals and aggregates; this will allow us to forward model the true lidar velocities from parameterizations. We also note that implicit in (2) is the assumption that the particle shape (or ensemble of shapes) does not change systematically as a function of size. Since we have taken a large sample of different clouds we expect any such correlation to average out; sensitivity studies would be valuable to back this up.

[25] For models which diagnose $N_0$ from T, coincident radar measurements may allow the parameterizations to be tested, since Z is related to $\lambda$ through $N_0$. The combination of Z, radar Doppler spectra and lidar Doppler velocity has the potential both to test parameterizations as a whole, and also to discriminate which elements of that parameterization are realistic and which are not. We aim to pursue this approach to evaluate the Met Office cloud scheme.

[26] **Acknowledgments.** We thank the staff at the Chilbolton Observatory for operation and maintenance of the Doppler lidar. This work was carried out under NERC grants NER/Z/S/2003/00643 and NE/EO11241/1.

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