Ice Cloud Particle Fall Velocity-Size Relations from Doppler Radar Measurements

S. Y. Matrosov
Cooperative Institute for Research in Environmental Sciences
University of Colorado
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

A. J. Heymsfield
National Center for Atmospheric Research
Boulder, Colorado

Introduction

Knowledge of ice cloud particle fall velocities as a function of the particle sizes is important for the development of remote sensing methods based on Doppler radar measurements and for an adequate representation of ice clouds in general circulation models. Unlike for water drops, the fall velocity-size relations for ice particles exhibit a significant variability due to changes in such properties as particle type, shape (habit), and density.

Until recently, the information about ice particle fall velocity-size (i.e., v_t - D) relations was obtained mostly through modeling using aerodynamic drag coefficients or from direct measurements (mainly for larger ice particles such as snowflakes). The results of such studies are usually expressed in a power law-form:

$$v_t = A\ D^B \qquad (1)$$

In this study, we use combined collocated measurements taken by a vertically pointed Doppler radar and infrared (IR) radiometer to measure the parameters of these relations remotely. We also analyze correlations between parameters in these relations (i.e., A and B) and particle characteristic size. Results of this study are also used for deriving relations between cloud ice water content (IWC) and mass-weighted fall velocities, V_m.

Variability of Theoretical Fall Velocity-Size Relations

For different habits of particles found in common ice clouds, the coefficient A and the exponent B in Eq. (1) were calculated using the aerodynamic approach. The calculation results are shown in Figure 1 where data are normalized for 8 km (air density 0.52 kg m^{-3}, temperature 236 K)—a typical altitude of high tropospheric ice clouds.

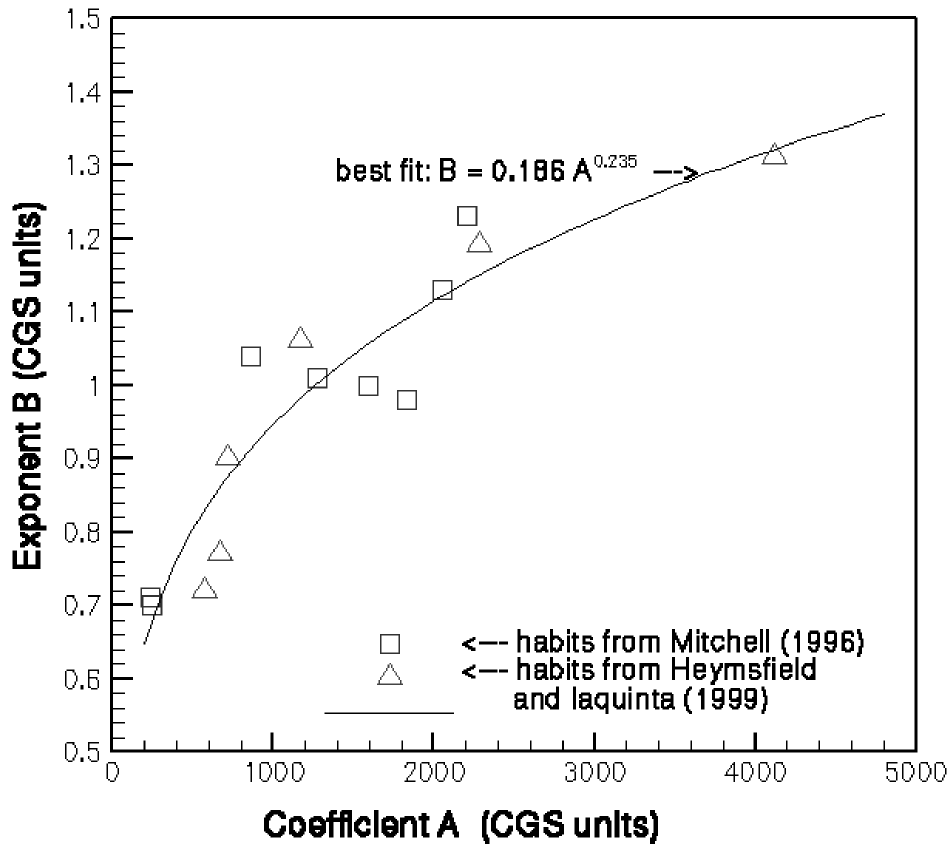

Figure 1. Correspondence between theoretical predictions of the coefficient and the exponent in Eq. (1).

Habits considered here were plates, branched crystals, side planes, and polycrystals from Mitchell (1996) and columns, single bullets, and bullet-rosettes from Heymsfield and Iaquinta (1999). There is a strong correlation between A and B (Figure 1), so it is sufficient to know just one coefficient (e.g., A) and express B as a function of A:

$$B \approx 0.186\, A^{0.235} \qquad (2)$$

Data in Figure 1 correspond to the fall regime of particles from a few tens of microns to about half a millimeter assuming that D in Eq. (1) is the equivalent spherical diameter. It can be seen from Figure 1 that for typical particles found in ice clouds, the coefficient A can vary more than one order of magnitude.

Correspondence Between Different Fall Velocities

Eq. (1) is written for an individual particle. However, of most practical interest are fall velocities representing the whole particle size distributions (PSD). Those fall velocities are the reflectivity-weighted fall velocities, (V_z), and the mass-weighted fall velocities, (V_m). Characterizing the whole PSD, one can define:

$$V_z = a_1 A D_o^B, \quad (3)$$

$$V_m = V_z / a_2 \quad (4)$$

here D_o is the median volume particle size characterizing the whole PSD.

Dimensionless coefficients a_1 and a_2 are introduced to describe a transformation from individual particle relations to those representing the whole PSD assuming that the particle population consists of crystals with similar habits. a_1 and a_2 depend on the details of PSD and also on D_o as a proxy of their dependence on particle bulk density. Figure 2 shows such dependencies for the PSD described by the gamma functions. For particle populations with D_o greater than about 80 μm (which is typical for many ice clouds seen by millimeter-wavelength radars) $a_1 \approx 1.3$ and $a_2 \approx 1.5$ with some variations due to details of the PSD. Since the ratio (a_1/a_2) is rather close to 1, the fall velocities-size relations for individual particles can be used as a proxy for such relations in terms of V_m and D_o describing the whole PSD.

Radar-Radiometer Method for Estimating IWC, D_o, and the Coefficient A

The radar-radiometer method developed at Environmental Technology Laboratory (ETL; Matrosov 1997) uses vertical profiles of radar reflectivity Z_e and Doppler velocity V_D measurements from radar and IR brightness temperature measurements from a radiometer to retrieve profiles of cloud ice water content (IWC) and D_o. In this method, measurements of V_D are used to estimate V_Z as described by Orr and Kropfli (1999). This method also allows retrievals of the layer-mean values of the coefficient A in the fall velocity-particle size relation. Figure 3 shows an example of such retrievals for one of the Atlantic Stratocumulus Transition Experiment (ASTEX) cirrus cases. Layer-mean values of the coefficient A estimated from remote measurements exhibit noticeable variability. These values are within theoretical predictions: 300 to 4000 (CGS units).

Figure 4 shows a scatter-plot of retrieved layer-mean values of the median mass particle size, D_m and the coefficient A. For most practical cases, $D_m \approx 0.8\ D_o$. There is a noticeable correlation between D_m and A, which is in general agreement with theoretical considerations. The rate of the fall velocity increase with particle size diminishes for large cloud particles.

Mass-Weighted Fall Velocity-Ice Water Content Relations

V_m-IWC relations are important for ice cloud representations in models. These relations describe the fallout rates that are greater than characteristic air motions if averaged over a significant amount of time. The radiative impact of ice clouds is determined, in part, by their temporal persistence, which is described using V_m-IWC relations. Figure 5 shows one example of deriving V_m-IWC relations experimentally using IWC values retrieved with the radar-radiometer method and V_m values estimated from measurements of vertical Doppler velocities. The V_m-IWC relations exhibit significant variability on a case-to-case basis.

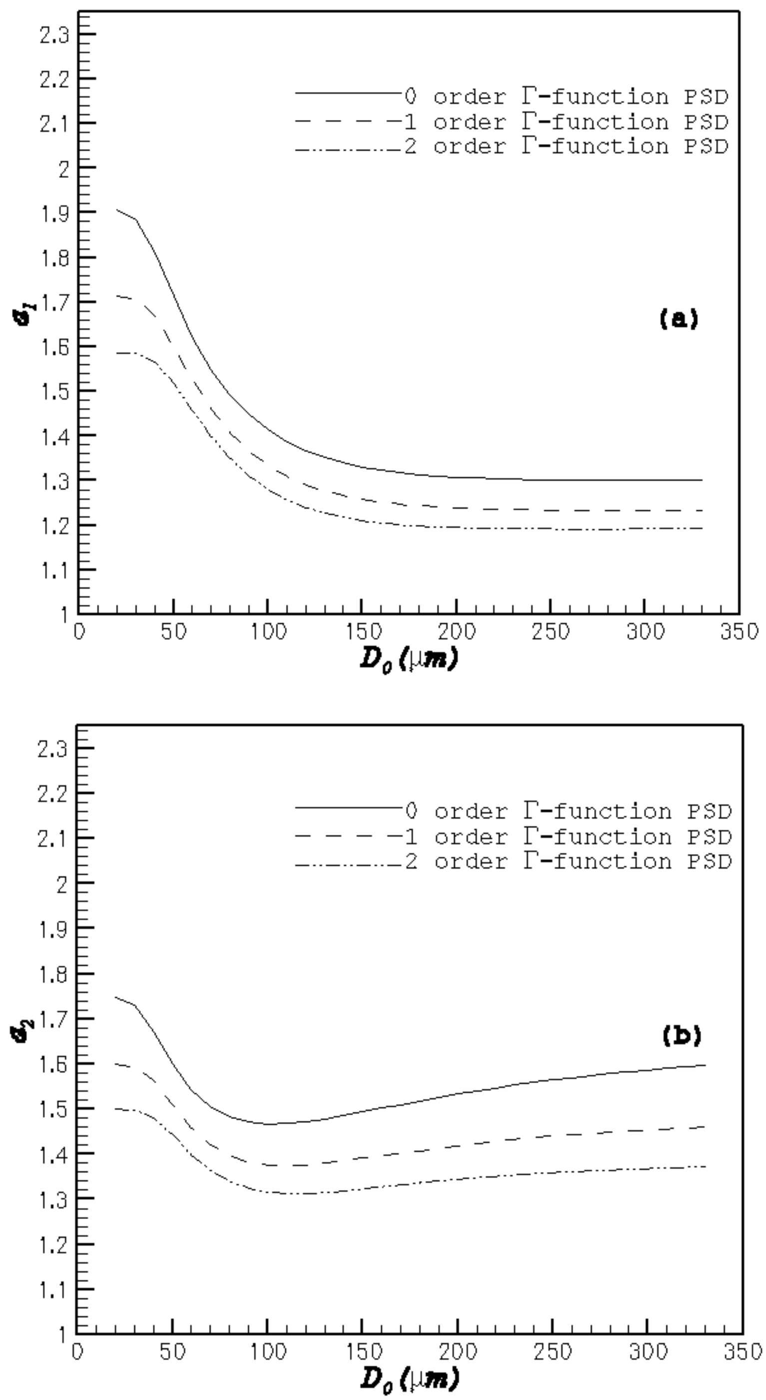

Figure 2. Transformation coefficients from individual particle fall velocity-size relations to those for PSD in terms of reflectivity-weighted fall velocity (a) and in terms of mass-weighted fall velocity (b).

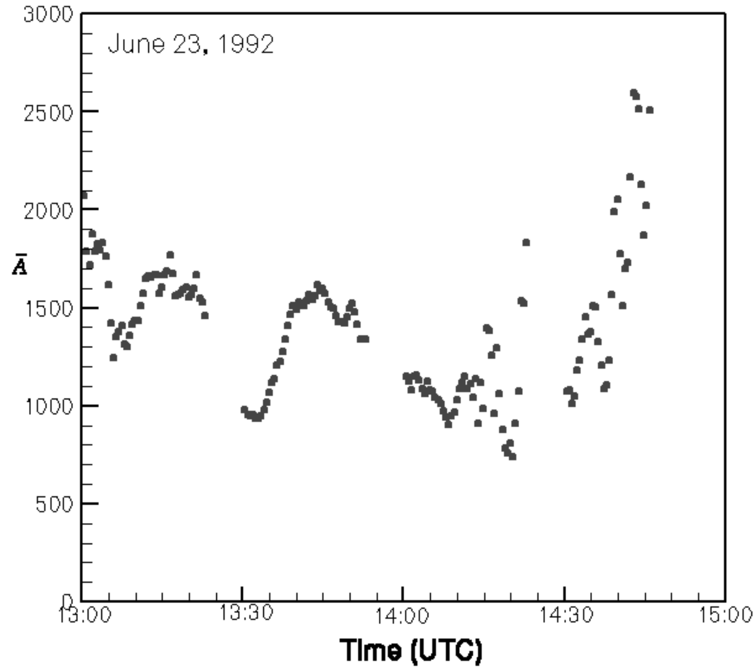

Figure 3. Time series of retrieved mean-layer values of the coefficient A for one of the ice cloud cases.

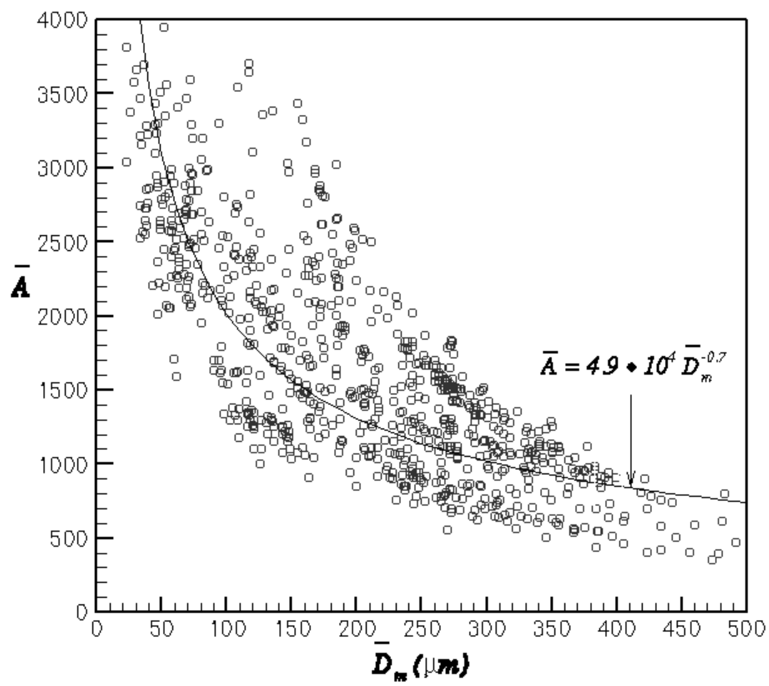

Figure 4. Scatter-plot of layer-mean values of the coefficient A and particle median mass size D_m.

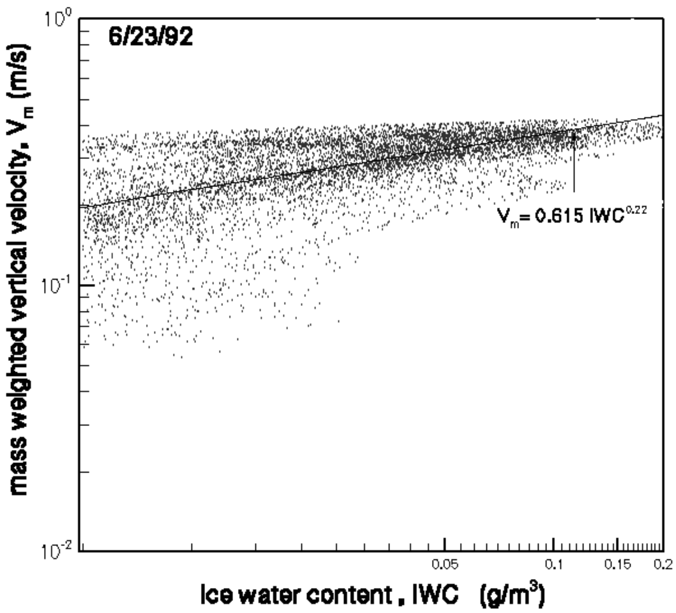

Figure 5. Scatter-plot of mass-weighted fall velocities versus cloud IWC.

Conclusions

Theoretical modeling shows that fall velocity-size relations for ice cloud particles vary in a wide dynamic range. The coefficient of these relations (expressed in a power-law form) can vary more than one order of magnitude depending on particle properties. The value of this coefficient determines largely the exponent, so these relations can be characterized just by one parameter (i.e., the coefficient A). Doppler radar measurements in combination with IR data can be used to estimate the coefficient A. Results of the experimental retrievals provide a range of variability for A, which is in good agreement with theoretical expectations. Experimental data indicate that there is an anti-correlation between the value of the coefficient in the fall velocity-size relations (for individual particles and for particle ensembles) and characteristic particle size. A good correlation also exists between mass-weighted fall velocities and cloud ice water content.

References

Heymsfield, A. J., and J. Iaquinta, 1999: Cirrus crystals terminal velocities. *J. Atmos. Sci.* Accepted.

Matrosov, S. Y., 1997: Variability of microphysical parameters in high altitude ice clouds: results of the remote sensing method. *J. Appl. Meteor.*, **36**, 633-648.

Mitchell, D. L., 1996: Use of mass- and area-dimensional power laws for determining precipitation particle terminal velocities. *J. Atmos. Sci.*, **53**, 1710-1723.

Orr, B. W., and R. A. Kropfli, 1999: A method for estimating particle fall velocities from vertically pointing Doppler radar. *J. Atmos. Oceanic Technol.*, **16**, 29-37.