Estimations of Cirrus Particle Fall Velocity-Size Relations from Radar Measurements

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Introduction

The representation of high-altitude ice clouds such as cirrus in general circulation models (GCMs) remains to be one of the uncertainties of these models. In addition to a better description of cloud microphysical parameters, another process that needs an improved parameterization in GCMs is the fallout of cirrus particles. This parameterization is based on the cloud particle fall velocity (v_t)-size (D) relations that are usually expressed by a power-law function. These relations have been studied both experimentally and theoretically based on calculations using drag-law equations for different flow regimes and particle habit (shape) information together with size-dependent estimates of such properties as the crystal mass and normal to the flow cross sectional area (e.g., Mitchell 1996). Experimental studies of the terminal fall velocity-size relations, however, are mostly limited to the ground observations of larger precipitating particles, although crystal properties in high-altitude ice clouds and those properties at the ground may differ significantly.

The use of millimeter wavelength Doppler radars provides a new powerful tool for measuring cloud properties. These radars by themselves and especially in combination with infrared (IR) and Microwave Radiometers can be used for remote sensing of ice cloud characteristic sizes and water contents (Matrosov 1997). In a vertical observation mode, the Doppler velocity measured by radar can be used to estimate cloud particle fall velocity (Orr and Kropfli 1999). In this study, the cloud particle median volume sizes (D_o) and reflectivity-weighted terminal fall velocities (V_Z) simultaneously estimated from remote measurements are used to construct fall-velocity-size relations, which can be used in models. These experimentally estimated relations are then compared to the theoretical calculations for different particle habits.

Theoretical Relations

For an individual particle, the terminal velocity as a function of its size is parameterized as

$$v_t = A D^B \tag{1}$$

where the coefficient A and the exponent B depend on particle habit and flow regime. Mitchell (1996) lists habit dependent coefficients of mass size and cross - sectional area size relations for most common cirrus particle sizes. We used these coefficients to calculate A and B for the flow regime when the Best (Devis) number, X, changes from 10 to 585. This regime corresponds to most common particle sizes found in cirrus ranging from about 50 µm to 500 µm in terms of the maximum crystal dimension.

As can be seen from Table 1, particles that are commonly found in cirrus clouds can exhibit a vast variety of fall velocity-size relations. The coefficient A varies as much as one order of magnitude for the main flow regime, though the exponent B shows more modest variability centering around 1.

Table 1. Parameters in the fall velocity-size power law for various particle types. Units are cgs.

Particle Type	A	B
Hexagonal plates	859	1.04
Hexagonal columns	1591	1.00
Rimed long columns	1835	0.98
Crystals with sector branches (Plb)	251	0.70
Broad-branched crystal (P1c)	242	0.71
Side planes (S1)	1279	1.01
Bullet rosettes (5 branches)	2211	1.23
Assemblanges of planar polycrystals	2050	1.13

For the small particle flow regime with Best number X between 0.01 and 10, coefficient A and the exponent B have a tendency to increase compared to values presented in Table 1. The opposite is true for the large particle flow regime with 585 < X < 156000. The relative increase of particle fall velocity with size becomes smaller for larger particles, in part because of the diminishing bulk density.

For an ensemble of particles, Eq. (1) can be generalized and the following relation for the reflectivity-weighted particle fall velocity and particle median size can be written as

$$V_z = A a_1 D_o^B \tag{2}$$

where a_1 depends on the details of the particle size distribution, and values of B and D_o. Figure 1 shows a_1 as a function of D_o for the typical range of B (0.7-1.3) and for several orders of the gamma function size distribution, n. Such distributions were assumed for this modeling since they have been shown to adequately describe most experimental size spectra of cirrus cloud particles (Kosarev and Mazin 1991).

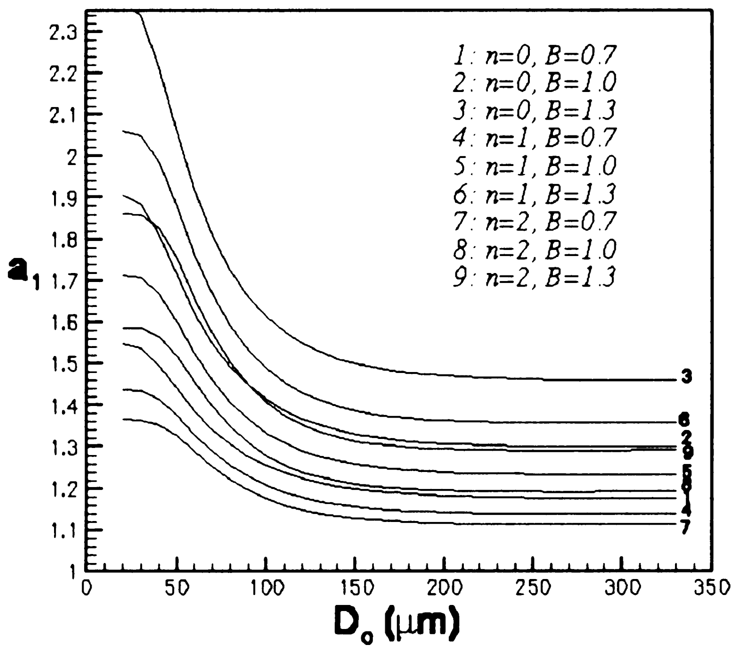

Figure 1. Coefficient a_1 in Eq. (2) as a function of cloud particle median size.

As can be seen from Figure 1 and Eq. (2), the transition from the fall velocity-size relation for an individual particle to that for the particle ensemble results in an effective increase of the coefficient of the power law by a factor between 1.1 and 2.3.

Experimental Measurements

The radar division of the National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) participated in several recent cloud field experiments with its K_a-band radar (λ = 8.66 mm), the narrow-band, Barnes-type IR radiometer (λ~10-11.4 μm) and the two-channel Microwave Radiometer (ν_1=20.6 GHz, ν_2=31.6 GHz). A number of cirrus and other ice clouds have been observed with the ETL instruments during these experiments.

The ETL radar-radiometer method for cirrus (Matrosov 1997; Matrosov et al. 1998) allows retrieval of such parameters as cloud particle median size and ice water content (IWC). In addition to these microphysical parameters, a layer-averaged value of the coefficient A is retrieved for each vertical beam of radar data and simultaneous estimate of cloud optical thickness from radiometric measurements.

Figure 2 (a, b) shows an example of such retrievals for two ice cloud cases: one from the priority cirrus event during FIRE-II (First ISCCP [International Satellite Cloud Climatology Program] Regional Experiment) and the other from the spring 1997 Atmospheric Radiation Measurement (ARM) Cloud Intensive Observation Period (IOP). Both clouds were pure ice phase clouds located between approximately 6 km and 11 km.

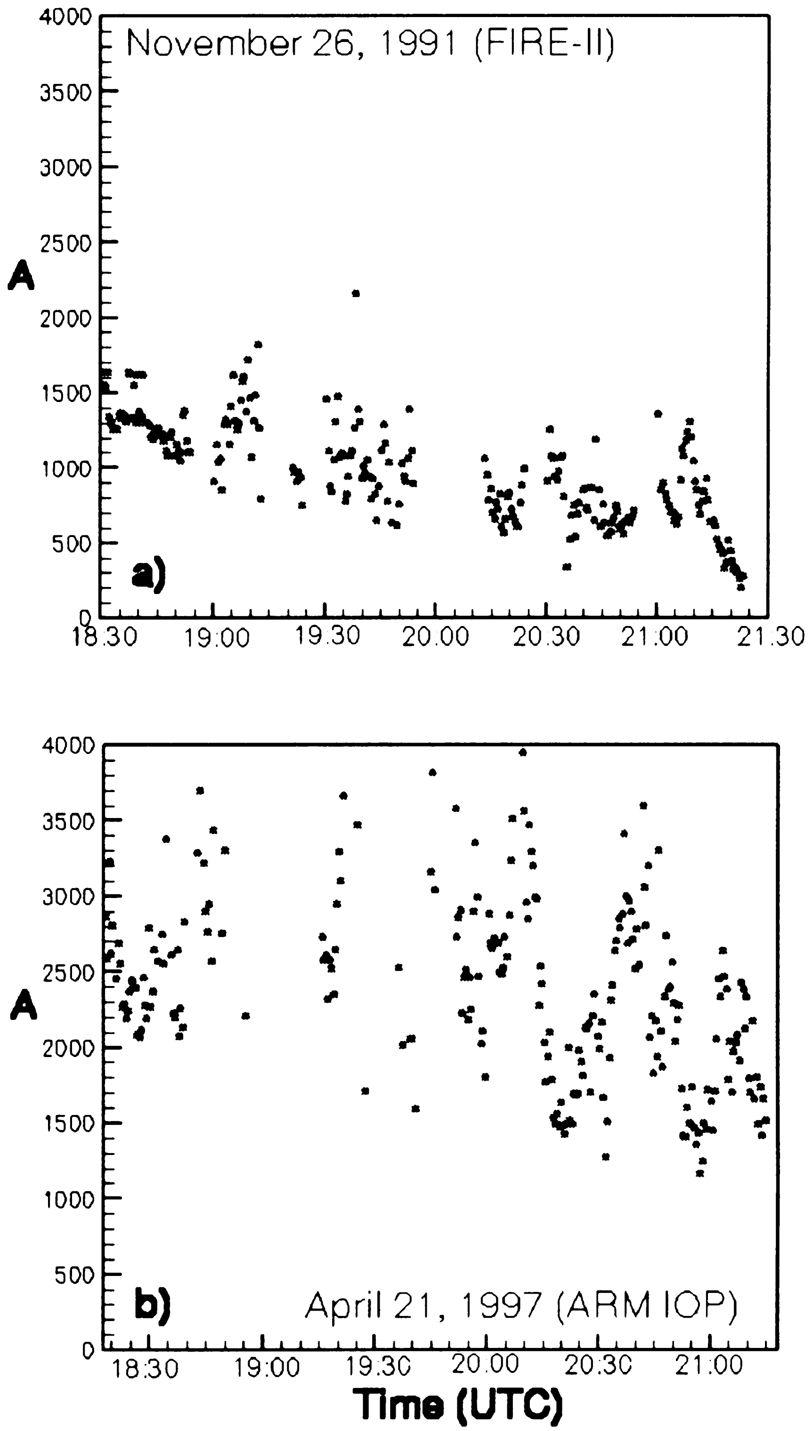

Figure 2. Retrieved values of the layer-mean coefficients A (cgs units) in the fall velocity-size relation.

During the retrievals, it was assumed that the particle size distribution could be described by the first-order gamma function, and that the exponent B in the fall velocity-size relation changes from 1.3 for the smallest median sizes detected in these clouds (~25 μm) to the largest ones (~500 μm). The latter assumption is important for estimating a_1 and is based on the theoretical calculations for different flow regimes as described in the previous section.

Values of A for the FIRE-II case are generally smaller than those for the ARM IOP case. Also, the former values exhibit less small-scale variability. The dynamic range of changes in A is from about 200 to almost 4000, which is in a good agreement with theoretical prediction (see Table 1).

Figure 3 (a, b) depicts the simultaneously retrieved layer-averaged values of cloud particle median sizes. The combined analysis of Figures 2 and 3 reveals a noticeable anti-correlation between characteristic particle size and the coefficient A. This fact is also in accord with theoretical calculations for different flow regimes. In spite of this anti-correlation, however, the median particle size does not determine a value for A unambiguously.

The two ice cloud experimental cases presented here are typical for many more observations. A significant variability of the coefficient A revealed by experimental data indicates that there is no unique fall velocity-size relation that can suit all modeling needs. Accounting for particle characteristic size can reduce but not eliminate a natural uncertainty of fall velocity-size relations.

Conclusions

Theoretical calculations and experimental retrievals by the remote sensing method using Doppler radar and radiometer measurements indicate a significant variability of the parameters in the power law relations between cirrus particle size and their fall velocities. The coefficient of these relations (A) can vary more than one order of magnitude from approximately 200 to almost 4000 (in cgs units), the typical values being between 1000 and 2000. The exponent in these relations (B) changes more modestly and usually is between about 0.7 and 1.3.

Both the coefficient A and the exponent B in the fall velocity- size relations tend to decrease as particle sizes increase. This tendency can be used for more accurate predictions of A in models that specify cirrus particle characteristic size.

Acknowledgments

In addition to ARM support, this research was funded in part through the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Project Science Office.

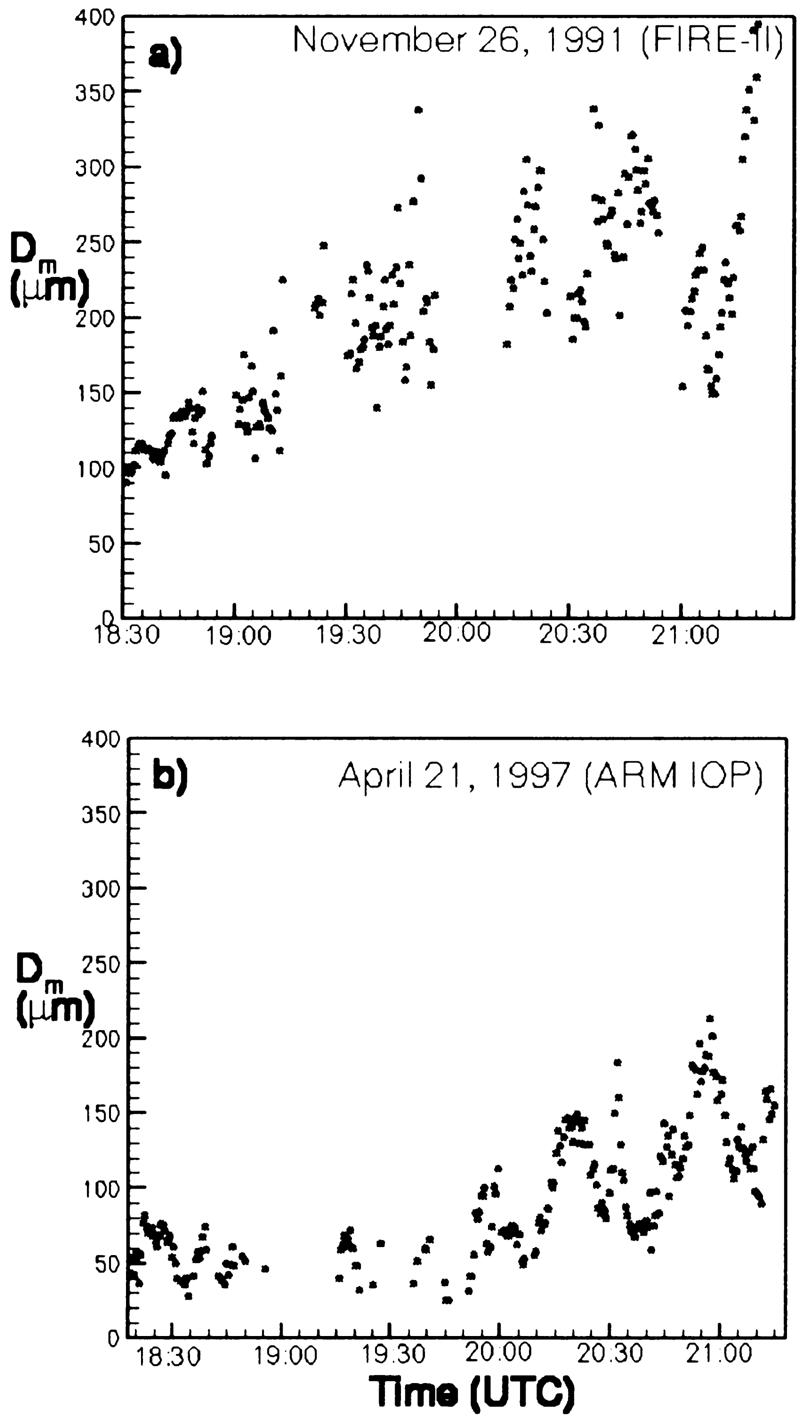

Figure 3. Time series of retrieved values of layer-mean particle median sizes.

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