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Estimation of Cirrus Cloud Particle Fallspeeds from Vertically Pointing Doppler Radar

Brad W. Orr and Robert A. Kropfli

325 Broadway
NOAA/ERL Wave Propagation Laboratory
Boulder, Colorado 80303

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1. Introduction

The First ISCCP Regional Experiment II (FIRE II) was conducted in Coffeyville, Kansas in late 1991 to study the microphysical and radiative properties of cirrus clouds. A variety of active and passive remote sensors were employed, including an 8-mm-wavelength cloud-sensing Doppler radar developed at the Wave Propagation Laboratory (WPL). The radar, having excellent sensitivity to cloud particles (-30 dBZ at 10 km), good spatial resolution (37 m), and velocity precision (.05 ms^{-1}), is an excellent tool for observing cirrus clouds (Kropfli et al., 1990; Martner and Kropfli, 1993). Having this radar directed toward the zenith for long periods of time during FIRE II permitted the reflectivity-weighted particle fallspeed to be related to reflectivity which allowed a separation of ice particle fallspeeds from vertical air motions. Additionally, such relationships have proved useful in other multi-sensor techniques for determining vertical profiles of ice particle characteristic size and ice water content in cirrus clouds (Matrosov et al., 1993). This paper discusses the analysis method and the results of applying it to cirrus cloud reflectivity and velocity data collected during FIRE II.

2. Methodology

Radial velocity data obtained by a vertically pointing Doppler radar (V_r) is the sum of the reflectivity-weighted hydrometeor fallspeed (V_t) and the vertical air motion (V_a).

$$V_r = V_t + V_a \, . \tag{1}$$

To arrive at relationships between radar reflectivity and reflectivity-weighted particle fallspeed, a straightforward method was devised. The underlying assumption is that an appropriately long temporal average of radial velocity will result in the air motion term being small compared to the fallspeed term in cirrus clouds. Although the optimal amount of averaging is a subject currently under investigation with combined wind profiler/cloud radar measurements, it is believed that an averaging time of 1-3 hr is suitable for most cirrus clouds. Under this assumption, the resulting averaged radial velocities will be due solely to particle motions ($V_r \approx V_t$). If this averaging is performed for various radar reflectivity intervals, a formula of the form

$$V_t = \alpha Z_e^{\beta} \tag{2}$$

can be derived where Z_e is the effective radar reflectivity and α and β are empirically determined constants. In order to ensure the representativeness of the resulting formula and account for spatial variation in particle habits and densities in the vertical, the averaging is performed over several height intervals within the cloud. Least-squares methods are then used to determine α and β at all levels within the cloud.

A variation of the above is a multiple-linear regression analysis that incorporates height as a proxy for the temperature dependence. This analysis requires Z_e to be given in decibels to account for the nonlinearity expressed in (2). The final product is one equation of the form

$$V_t = a + b(10\log Z_e) + c(h) \, , \tag{3}$$

where a, b, and c are constants derived from the linear regression of the averaged Doppler velocity against reflectivity (dBZ) and the height, h, (or temperature). An advantage of this method is that both the reflectivity and height dependencies of hydrometeor fallspeeds are incorporated into one equation. (2), on the other hand, requires one formula for each height or a secondary analysis to determine height dependencies of α and β.

3. Discussion

Figure 1 is a 3-hr time-height display of reflectivity (dBZ) from a cirrus cloud observed on 25 November, 1991 during FIRE II. Time increases from left to right, and height is given in km AGL on the right side. The results of (2) applied to this time period are shown in Fig. 2. The individual curves were derived from 3-hr averages corresponding to Fig. 1 over height intervals of approximately 560 m. The resolution in Z_e is equivalent to 1 dB. A minimum of 300 velocity estimates, each acquired over a 3-s dwell, was required at each point in Fig. 2 before the least-squares analysis was performed. This threshold was determined by noting the magnitude of the improvement in the curve-fitting result as higher threshold values were imposed. Noteworthy features in Fig. 2 are the systematic vertical variation of the derived relationships and the small scatter about the best fit curves. The standard deviation about each curve in Fig. 2. was less than 4 cm s^{-1}. Note that although the entire record was 3 hr in length, the top level of the cloud was dissipating so that the effective averaging time for that level was on the order of only 1 h. The scatter of data about the best fit curve seems unaffected by the reduced averaging time, however.

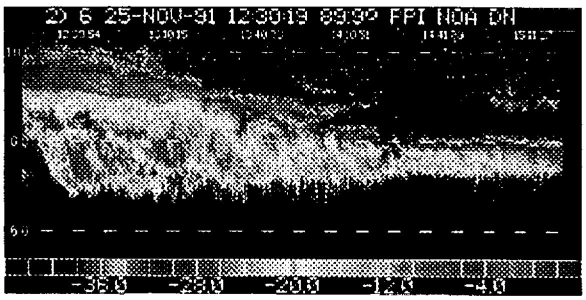

Figure 1. Time-height display of cirrus cloud reflectivity (dBZ) from vertically pointing radar data, 12:30 -15:30 UTC 25 November, 1991. Vertical scale is km AGL.

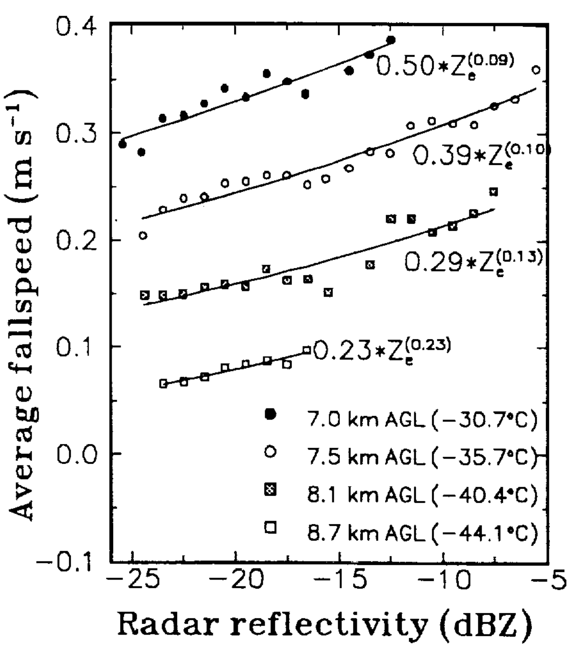

Figure 2. Power law fit of data in Fig. 1 using (2).

Several other data sets, spanning three days from the FIRE II data set, have been analyzed in a similar manner. The general trend of higher fallspeeds at cloud base is evident in all cases, although the vertical stratification is not always as well defined as in Fig. 2. This result is consistent with the notion that the larger and/or denser particles are found in the lower portions of cirrus clouds. Fallspeeds obtained from all three data sets ranged from 0.05 m s^{-1} up to 0.9 m s^{-1} over a height range of 6.0 to 10.0 km AGL which is within the expected range of values for cirrus cloud particles (Pruppacher and Klett, 1978).

Values for α and β covering three different days ranged from 0.21 to 0.87 and from 0.05 to 0.24, respectively. The results are summarized in Fig. 3. For a given analysis period, there was typically a large variation in α with height. However, although β remained relatively constant during a given analysis period, it was seen to vary considerably from case to case. A general trend can be seen in the results from 22 and 25 November (Fig. 3). The 26 November case, however, exhibits a different characteristic in the α and β values. Microphysical data also indicate significant differences. A bimodal distribution is evident on November 26, while the other two cases are more representative of single mode distributions (Miloshevich, L., (NCAR/MMM), personal communication, November, 1992).

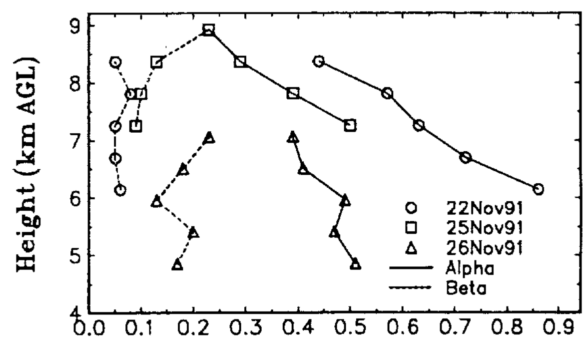

Figure 3. Vertical variations in α and β where β is dimensionless and α has dimensions of (m s^{-1})(mm^6 m^{-3})$^\beta$.

Heymsfield (1975) arrived at a relationship similar to the above using combined radar and aircraft observations of a cirrus uncinus generating cell. His values for α and β were 0.84 and 0.074, respectively. Heymsfield (1977) presents results for stratiform ice clouds with α values between 0.59 and 0.67, and β ranging from 0.06 to 0.095. The K_a-band results are in general agreement with these results, although the spread in our data is somewhat larger.

Figures 4 and 5, respectively, show a 24-min average of vertical velocity data before and after removing the particle fallspeed contribution. These data are from a cloud system that persisted for over 12 h. A multiple-linear regression analysis of the form shown in (3) was used for these data in order to more easily incorporate the height dependencies. Figure 4 was obtained by applying (4) to the data in Fig. 3:

$$\boldsymbol{V_t = 0.6644 + 0.0112(10\log Z_e) - 0.0349(h)}\,. \quad (4)$$

The fallspeed correction was applied on a beam-by-beam basis and an average was then performed over the 24-min period. The vertical air motion in Fig. 4 shows upward motion throughout most of the cloud and with a peak value of 0.13 m s^{-1} near the cloud center.

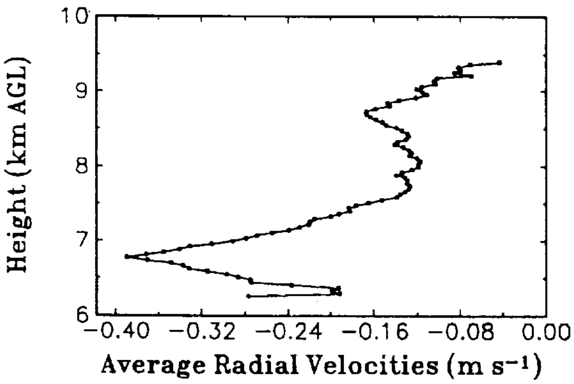

Figure 4. 24-min average of vertically pointing Doppler radial velocities (m s^{-1}) beginning 19:00 UTC on 26 November, 1991.

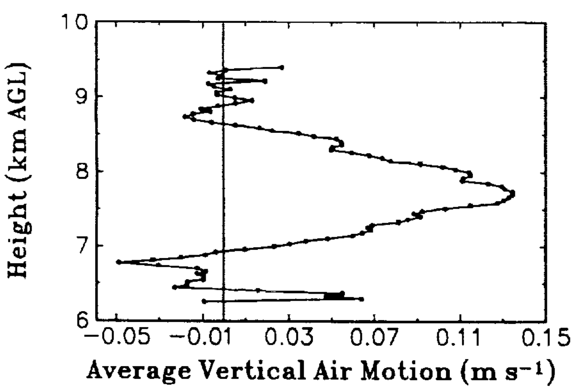

Figure 5. 24-min average air motion (m s^{-1}) beginning 19:00 UTC on 26 November, 1991. Derived from Fig. 4 after using (4).

4. Conclusions

A method has been demonstrated that allows the estimation of hydrometeor fallspeeds within cirrus clouds from a vertically pointing Doppler radar. These initial results are supported by other theoretical and observational studies, which lends promise to this technique. Continuing studies will include the application of improved data thresholding schemes over the larger data set acquired in FIRE II and other programs. Comparisons with in situ observations will also be performed.

5. Acknowledgments

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