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MICROPHYSICAL PROPERTIES OF THE NOVEMBER 26 CIRRUS CLOUD RETRIEVED BY DOPPLER RADAR / IR RADIOMETER TECHNIQUE

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1. INTRODUCTION

Gaining information about cirrus cloud microphysics requires development of remote sensing techniques. In an earlier paper, Matrosov et al. (1992) proposed a method to estimate ice water path (IWP)(i.e., vertically integrated ice mass content IMC) and characteristic particle size averaged through the cloud from combined ground-based measurements of radar reflectivities and IR brightness temperatures of the downwelling thermal radiation in the transparency region of 10-12 µm. For some applications, the vertically averaged characteristic particle sizes and IWP could be the appropriate information to use. However, vertical profiles of cloud microphysical parameters can provide a better understanding of cloud structure and development.

Here we describe a further development of the previous method by Matrosov et al. (1992) for retrieving vertical profiles of cirrus particle sizes and IMC rather than their vertically averaged values. In addition to measurements of radar reflectivities, the measurements of Doppler velocities are used in the new method. This provides us with two vertical profiles of measurements to infer two vertical profiles of unknowns, i.e., particle characteristic sizes and IMC. Simultaneous measurements of the IR brightness temperatures are still needed to resolve an ambiguity in particle size - fall velocity relationships.

2. THEORETICAL CONSIDERATIONS

Doppler velocities, V_m, measured with the vertically pointed radar antenna represent the sum of reflectivity-weighted particle fall velocities, V_f, and of vertical air motion, V_a:

$$V_m = V_f + V_a. \tag{1}$$

To extract values of V_f from measured quantities V_m, we used an approach based on the assumption that, over time intervals of 1 - 2 hours, the mean vertical air motion in a cloud is small compared to fall velocities of ice particles. Thus, the observed average value of Doppler velocity closely approximates V_f (Orr and Kropfli 1993). Averages were performed for 1 dB reflectivity intervals to find reflectivity- fall velocity relationships at different range gates to get estimates of V_f at the same time intervals as those of reflectivity. Our experience with Doppler velocity data processing shows that changing the averaging time from 1 hour to 2 hours usually does not cause significant variations in estimated values of fall velocities V_f, which demonstrates the soundness of this approach.

The largest dimensions of ice particles in cirrus clouds usually do not exceed $D_{max} \approx 2$ mm (Dowling and Radke 1990), which is still within the Rayleigh scattering regime for radar frequencies up to the Ka-band (Yeh et al. 1982). In this regime, backscattering cross sections of individual particles increase with the sixth power of particle characteristic size. After integrating these cross sections with the particle size distribution, we get, for the radar reflectivity with respect to ice, Z_i,

$$Z_i = f_i C D_m^6, \tag{2}$$

where C and D_m are particle concentration and median diameters, respectively, and the coefficient f_1 depends on the particle size distribution. Hereafter, we assume that this distribution is the gamma function of the first order. This function adequately describes many experimental size spectra of cirrus cloud particles (Kosarev and Mazin 1989). For the first order gamma function, $f_1 \approx 0.486$ if Z_i is in cm^3, C is in cm^{-3}, and D_m is in cm. Equation (1) implies that particles are spherical. Effects of nonsphericity, however, can be approximately taken into account by tuning the coefficient f_1.

Integrating over the distribution, we can obtain also the expression for IMC as follows:

$$\mathrm{IMC} = f_2 C D_m^{\,3}, \tag{3}$$

where $f_2 \approx 0.111$ if the size distribution is the first order gamma function and IMC is in g cm^{-3}.

From (2) and (3) one can see that finding vertical profiles of particle sizes and IMC is equivalent to having estimations of C and D_m at each radar range gate. Equation (2) provides one vertically resolved relationship between the measured values (i.e. Z_i) and the unknowns. A second relationship should connect these unknowns and the particle fall velocity estimates.

Particle fall velocity V_f is the reflectivity-weighted velocity of individual particles in the radar resolution volume, v_f:

$$V_f = \int_0^{D_{max}} v_f N(D) D^6 dD / Z_i, \tag{4}$$

where $N(D)$ is the size distribution function.

Experimental studies of the fall velocities of individual ice crystals demonstrate that fall velocity-size relationships can be approximated by the power law function (Pruppacher and Klett 1978):

$$v_f = A D^B, \tag{5}$$

where A and B are constant for a particular crystal shape. According to the data presented by Pruppacher and Klett (1978), the coefficient B generally varies from 0.8 to 1.3. The coefficient A shows much greater variations, up to two orders of magnitude.

Integrating according to (4) gives the following expression for V_f estimates:

$$V_f = A f_3 D_m^{\,B}. \tag{6}$$

The coefficient f_3 depends slightly on D_m, but this dependence is negligibly small. The value of f_3 depends also on B. For the first-order gamma function and B=1, $f_3 \approx 1.71$ if V_f is in cm s^{-1}.

Equation (6) provides the second vertically resolved relationship between the measurables and unknowns. Given relatively low variations of B, we can reasonably assume that $B \approx 1$. However, possible large variations of A indicate that the value of this coefficient has to be estimated from at least one additional measurement.

A measurement for estimating A is obtained from the brightness temperature of cloud downwelling thermal radiation. Matrosov et al. (1992) proposed a technique to infer cloud optical thickness due to extinction from brightness temperature measurements in the IR "window" region by a narrow-band IR radiometer. In this region, cirrus particle size factors ($\pi D/\lambda$) are large compared to the wavelength, and we can assume that particle extinction efficiency is close to 2. In this case, the cloud extinction coefficient α and the optical thickness τ can be expressed as follows:

$$\alpha = f_4 C D_m^{\,2}, \tag{7}$$

and

$$\tau = \sum_j (f_4 C D_m^{\,2})_j \Delta h_j, \tag{8}$$

where the summation is with respect to range gates Δh_j and $f_4 \approx 0.432$ if α is in cm^{-1}.

At the first step of the retrieval cloud microphysical parameters for each radar beam, we assume some initial value for A. Then, from estimates of fall velocities V_f, we retrieve values of particle sizes D_m from (6) at each range gate. Knowing D_m allows calculations of particle concentrations C from reflectivity data using (2). After that, the value of optical thickness τ is calculated using (8) and compared with the actual value from the IR radiometer measurement for the considered radar beam. From the ratio of the calculated and measured values of optical thickness we find a corrected value of A for which the newly calculated and measured values of τ would coincide. The corrected value of A is then used to calculate final vertical profiles of particles sizes, concentrations, and IMC using (6), (1), and (3).

3. EXPERIMENTAL EXAMPLE

We use experimental data obtained during the FIRE-II experiment to illustrate the proposed method. One of the priority dates was November 26, when a slowly developing cirrus cloud was seen over a time period of several hours. Radar data were taken by the Wave Propagation Laboratory (WPL) Doppler 8.6 mm wavelength radar with the antenna pointing vertically. This radar was able to measure vertical velocities with an accuracy of about 5 cm s^{-1}. IR brightness temperatures were measured with a modified Barnes narrow angle radiometer (PRT-5), which had a wavelength band from 9.95 to 11.43 μm. Water amount was obtained from WPL's two channel microwave radiometer (working at frequencies of 31.65 GHz and 20.6 GHz) to account for the atmospheric transparency and thermal radiation when retrieving optical thickness values from IR brightness temperatures using the technique described by Matrosov et al. (1992).

Figure 1 shows a time height cross section of the retrieved particle median diameters (D_m). It can be seen that larger particles are mostly located in the lower part of the cloud. Particles are generally getting larger as the cloud becomes thicker and gradually descends. For the first order gamma function size distribution, the relationship between the median diameter and the effective radius (r_e), another widely used characteristic size of cloud particles, is the following: $r_e = 0.46 \cdot D_m$.

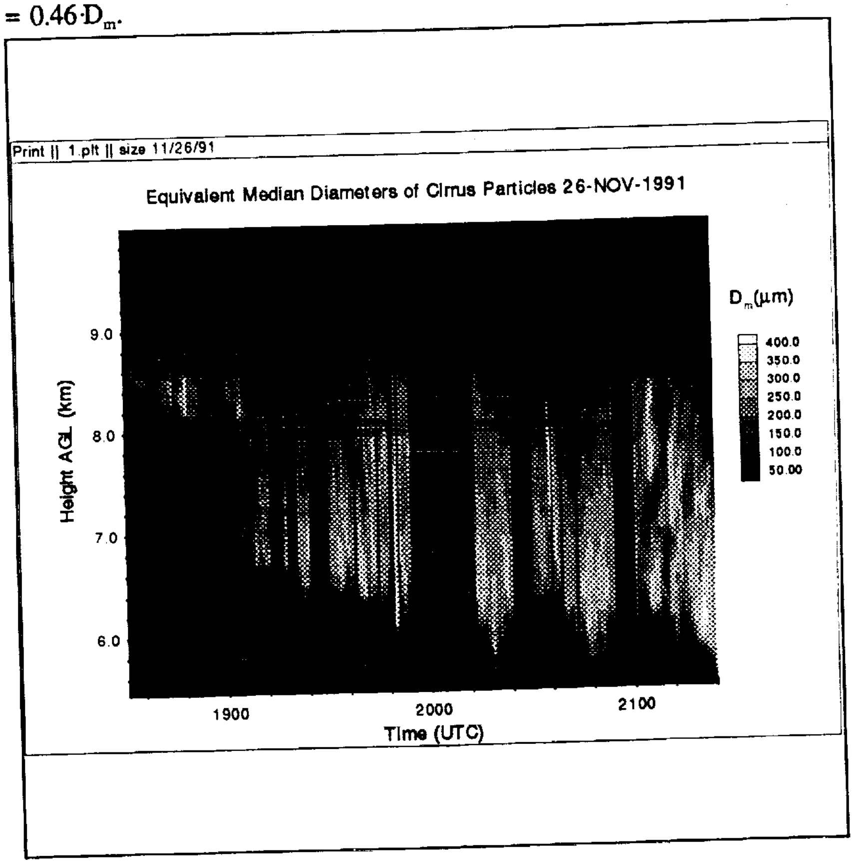

Figure 1. Time height cross section of cirrus particle median diameters observed on November 26, 1991

Figure 2 shows a time height cross section for retrieved values of particle concentrations. The highest particle number densities are in the upper part of the cloud. However, the sizes of these particles are small. As particles descend through the cloud, they grow larger and their concentrations decrease.

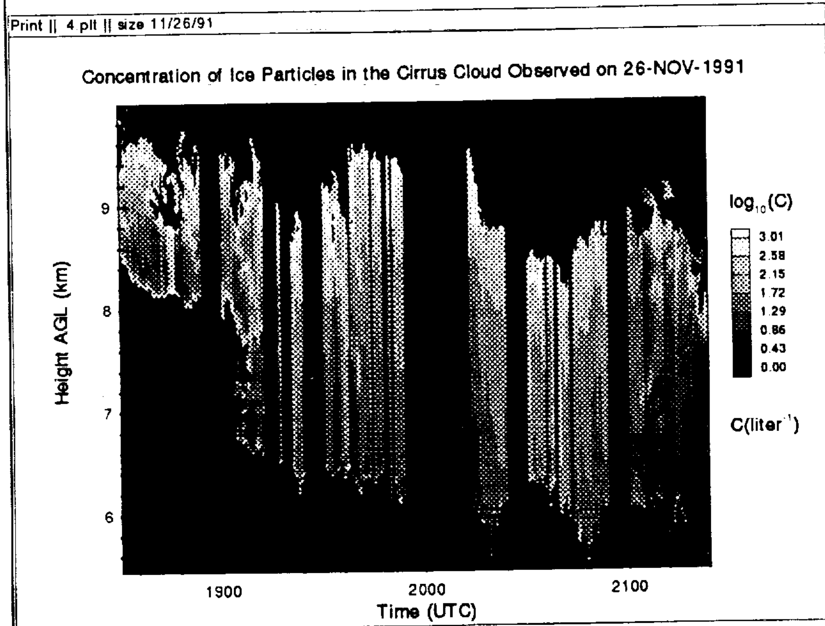

Figure 2. Time height cross section of cirrus particle concentrations observed on November 26, 1991.

The size information obtained using the radar/IR radiometer technique is in general agreement with the lidar/radar technique and data of direct measurements (Intrieri et al. 1993). Knowing characteristic sizes, concentrations and terminal velocities of particles one can easily calculate some other parameters of cloud microphysics such as vertical profiles of ice mass content and ice mass flux. Integrating vertical profiles of ice mass content provides values of ice water path which is important for longwave cloud feedback (Ebert and Curry, 1992). Our future plans include retrieving and studying information about aforementioned parameters and estimating possible retrieval errors.

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