Doppler Radar and Microwave Radiometer Derived Stratus Cloud Particle Size Distributions

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Introduction

Some earlier studies demonstrate that the size distribution of stratus cloud particles can be retrieved using radar reflectivity factor from millimeter-wave cloud radar and liquid water path estimated from microwave radiometer radiance measurements (White et al. 1991; Frisch et al. 1995, 1998). One source of error in these retrievals is the use of a climatological value for the geometric standard deviation (Miles et al. 1999). In this paper, we discuss an alternative retrieval method that incorporates the median radius of the cloud particle number concentration (count median radius, Hinds 1982), as opposed to the geometric standard deviation. The algorithm retrieves vertical profiles of liquid water content, number concentration, and effective radius using vertical profiles of radar reflectivity factor, Doppler velocity, and estimated particle median radius, together with integrated liquid water path. The advantage of this approach is that it does not rely on climatological values and that the extinction coefficients computed from retrieved size distribution are less sensitive to errors in median radii as opposed to geometric standard deviations. The retrieved values are also less sensitive to instrumental errors compared with the algorithm given by Frisch et al. (1995, 1998).

Proposed Algorithm

Since radar reflectivity factor and liquid water content are proportional to the sixth and third moment of the cloud particle size distribution (White et al. 1991; Frisch et al. 1995), respectively, the reflectivity factor, Z_i, for the *i*th sample volume is

$$Z_i = 2^6 N_i r_{ni}{}^6 \exp(18 \ln^2 \sigma_{gi}), \tag{1}$$

and the liquid water content, q_i, for the *i*th radar sample volume is

$$q_i = \frac{4}{3}\pi\rho_w N_i r_{ni}{}^3 \exp\left(\frac{9\ln^2\sigma_{gi}}{2}\right), \tag{2}$$

where N is the number concentration, σ_{gi} is the geometric standard deviation, r_{ni} is the median radius, and ρ_w is the density of liquid water. Eliminating σ_{gi} from Eqs. (1) and (2), we obtain

$$q_i = \frac{\sqrt{2}}{3}\pi\rho_w N_i{}^{3/4} r_{ni}{}^{3/2} Z_i^{1/4}. \tag{3}$$

When the liquid water contents, q_i, are summed over all radar sample volumes with height, Δz_i, the liquid water path, Q, becomes

$$Q = \frac{\sqrt{2}}{3}\pi\rho_w N_i{}^{3/4} \sum_{i=1}^{n_c} r_{ni}{}^{3/2} Z_i^{1/4}\Delta z_i, \tag{4}$$

where the number concentration, N, is assumed to be constant with height. Eliminating N using Eqs. (3) and (4), we obtain

$$Q_i = Q\frac{r_{ni}{}^{3/2} Z_i^{1/4}}{\sum_{j=1}^{n_c} r_{nj}{}^{3/2} Z_j^{1/4}\Delta z_j}. \tag{5}$$

For a lognormal distribution, the effective radius is

$$r_{ei} = r_{ni}\exp(2.5\ln^2\sigma_{gi}). \tag{6}$$

Combining Eqs. (1), (2), and (6) leads to

$$r_{ei} = r_{ni}^{4/9}\left(\frac{\pi\rho_w Z_i}{48 q_i}\right)^{5/27}. \tag{7}$$

Estimate of Median Radius

When r_{ni} is proportional to $Z_i^{1/6}$, the liquid water content retrieved by this algorithm is the same as that retrieved by the algorithm given by Frisch et al. (1995). Ovtchinnikov and Kogan (2000) obtained a relation between liquid water content and reflectivity factor as

$$q_i = aZ_i^{0.76}, \tag{8}$$

based on their large eddy simulation model where a is an unknown parameter determined experimentally. Their relation indicates that r_{ni} is proportional to $Z_i^{1/3}$. These relation provides the liquid water content that does not depend on the radar calibration error. However, these proportionality can vary geographically and temporally. Moreover, a in Eq. (8) has to be known to retrieve the effective radius and number concentration.

We use the variance of the Doppler velocity computed from the first moment of the Doppler spectrum over a 30-min time period and the statistical model given by Considine and Curry (1996). The model suggests that

$$r_{ni} = 13.2\overline{ww}_i^{1/4}, \tag{9}$$

for low stratus clouds where $\overline{ww}_i$ is the vertical velocity variance estimated from a Doppler radar (Kato et al. 2000).

Retrieval Results

We used data collected at the Southern Great Plains central facility (Lat. 97.48W, Lon. 36.69N) on December 3, 1997, to retrieve the size distribution of stratus cloud particles. Reflectivity factors and Doppler velocities were measured by the Atmospheric Radiation Measurement (ARM) 35-GHz Doppler radar operated as a part of the ARM Program (Moran et al. 1998; Clothiaux et al. 1999). The liquid water content is retrieved from microwave radiometer measurements by the algorithm developed by Liljegren (1995). Figure 1 shows the retrieved liquid water content, effective radius, and number concentration. Increasing the liquid water content and effective radius with height is evident in Figure 2, which shows horizontal averaged these values as a function of cloud height fraction: both the liquid water content and effective radius increases with height through the lower one-half to two-thirds of the cloud height.

Irradiance Computations

To evaluate the reasonableness of the retrieved microphysical properties, we input them into two radiative transfer models and compared the results with observations. To this end, we used delta two- and four-stream radiative transfer models to compute the downward longwave and shortwave surface irradiance, respectively, using the retrieved number concentrations and effective radii as input to these models. We computed the optical properties of the cloud particles according to Mie theory using the retrieved effective radius and a geometric standard deviation of 1.42 to specify the parameters of a lognormal distribution.

In the radiative transfer calculations, gaseous absorption was computed using the k-distribution method and correlated-k tables developed by Kato et al. (1999) and Mlawer et al. (1997) for shortwave and longwave radiation, respectively. Rawinsondes provided atmospheric water vapor profiles for both case study periods, while we estimated the shortwave surface albedo from the ratios of upward to downward pointing pyranometer measurements. The average surface albedo between 1800 Universal Time (UT)

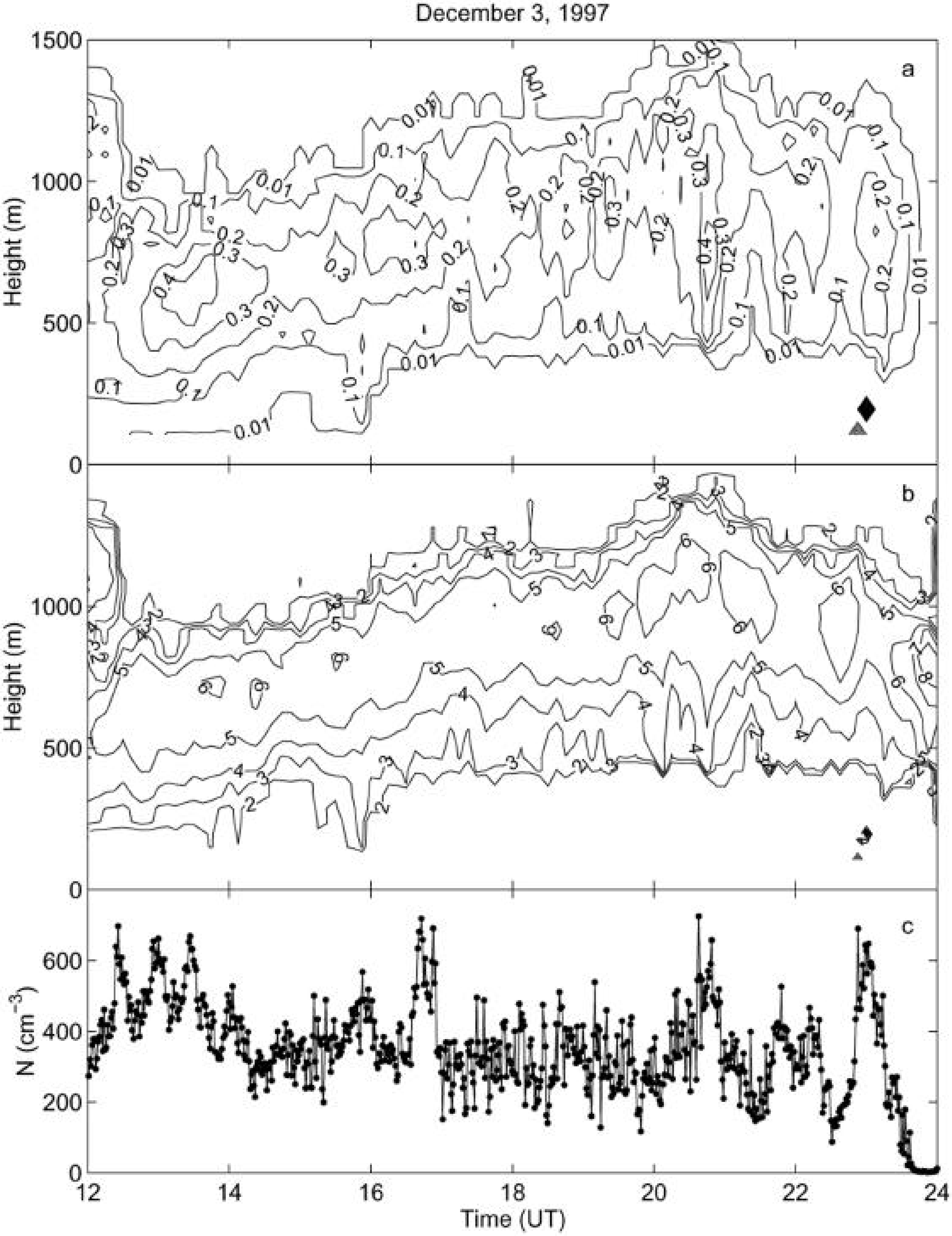

Figure 1. Retrieved (a) liquid water contents, (b) effective radii, and (c) number concentrations for December 3, 1997. The radar reflectivity factor is averaged every 7.5 min to produce the contour plot. The contour interval in (a) is every 0.1 g m^{-3} and numbers indicate the liquid water content in g m^{-3}. The contour interval in (b) is every micrometer and numbers indicate the radius in μm.

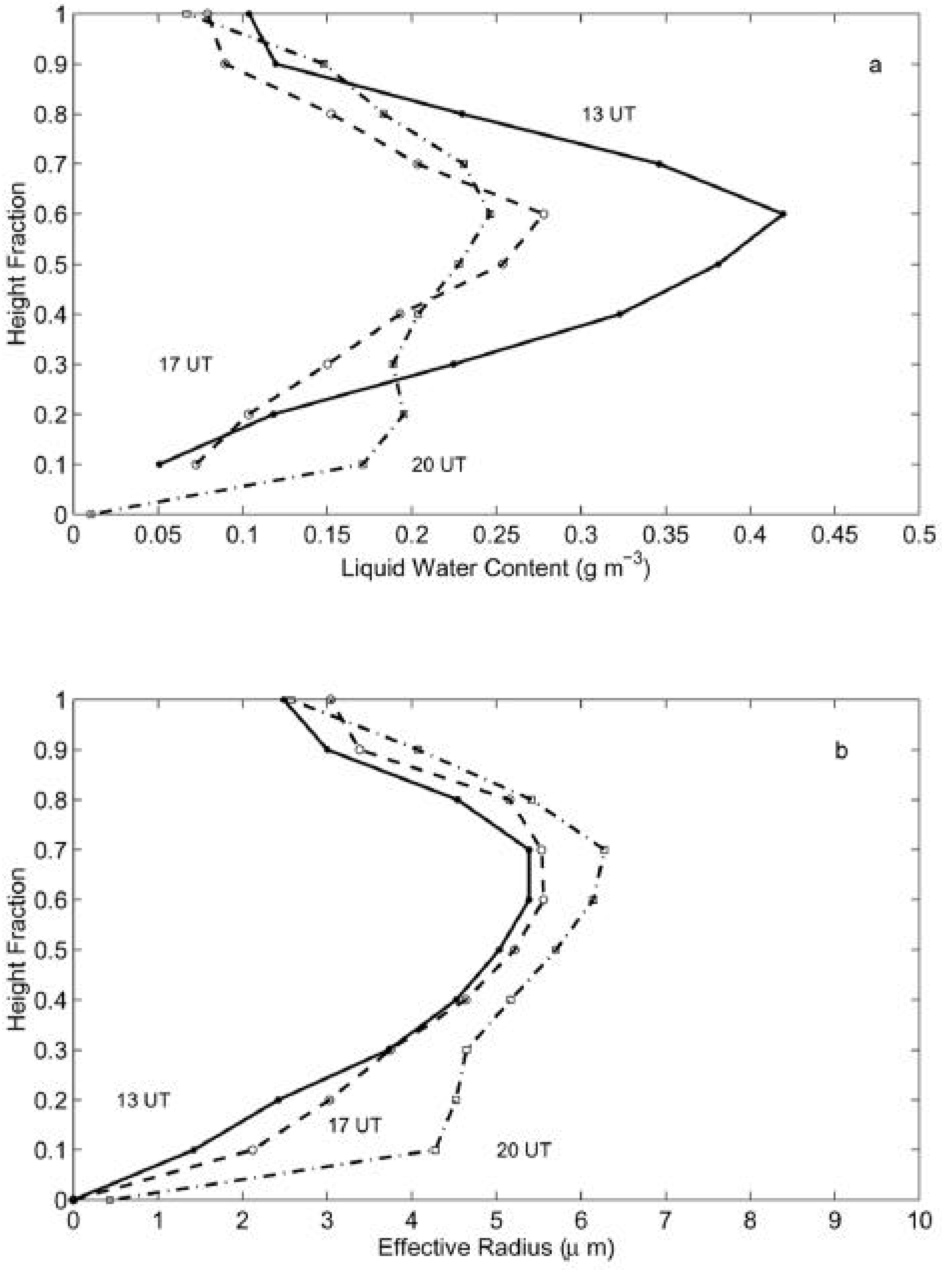

Figure 2. (a) Vertical profile of the liquid water content and (b) effective radius for December 3, 1997. Ordinates are the fraction of the height relative to the cloud depth.

and 2100 UT was 0.174. We assumed the surface emissivity to be unity and used the surface air temperature for the surface temperature. Both the downward shortwave and downward longwave irradiances were computed at 1-minute intervals over the two case study periods.

The resulting downward shortwave surface irradiances are well correlated with the measured irradiances throughout the 8-hour period from 1400 UT to 2200 UT (Figure 3). On average, the modeled shortwave irradiance is smaller by 6.3 Wm^{-2} than the measurements. These amounts correspond to 8% of the averaged measured downward shortwave irradiance. The modeled longwave irradiance is smaller by 0.7 Wm^{-2} than the measurements, which corresponds to 0.2% of the averaged measured downward longwave irradiance.

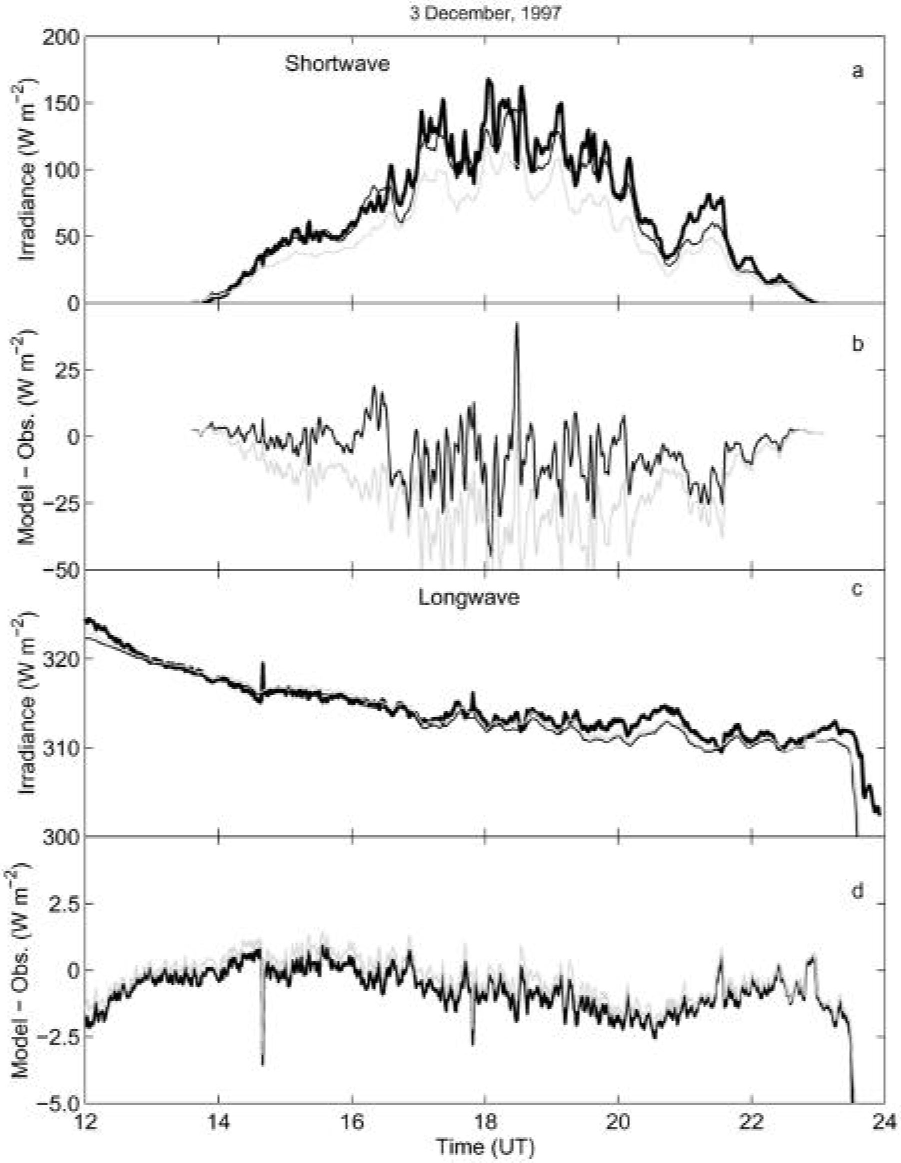

Figure 3. Measured (thick line) (a) shortwave and (c) longwave downward irradiance. The thin and shaded solid lines indicate the modeled irradiance with retrieved size distributions and with 5.4 μm effective radius, respectively. The retrieved effective radius and concentration were used to compute the irradiance for every minute. (b) (shortwave) and (d) (longwave) show the difference of the modeled irradiance with retrieved size distribution (thick solid line) and with 5.4 μm (shaded line) from the measurements.

For the comparison, we also used the effective radius of 5.4 μm, which is the average effective radius for continental stratus clouds reported by Miles et al. (1999), to compute the downward shortwave and longwave surface irradiance. The liquid water was uniformly distributed from the observed cloud base to the top. The computed irradiance with the average effective radius is also well correlated with measurements, which implies that the variation of the shortwave surface irradiance is mainly caused by the variation in the liquid water path. On average, the modeled shortwave irradiance with the average effective radius is smaller by 23 Wm^{-2} than the measurements. While Dong et al. (1999) reported a substantial variation in the effective radius over two years at the site (4 μm to 14 μm), using the effective radius of 5.4 μm for computing downward irradiance does not introduce a significant bias error for these two cases because the retrieved effective radii are close to the average effective radius.

Summary

This paper demonstrates that number concentration and vertical profiles of liquid water content and effective radius can be retrieved using liquid water path estimates and vertical profiles of radar reflectivity factor and Doppler velocity. An important feature of the proposed retrieval is that the height dependence of the median radius, r_{ni}, of the cloud particle size distribution is estimated from vertical Doppler velocity measurements obtained by a 35-GHz cloud radar. Although most of the variations in downward shortwave irradiances at the surface are caused by variations in the liquid water path, using retrieved cloud particle size distributions improve computation results from those using a climatological value.

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