Vertical Profiles of Continental Stratus Cloud Properties Retrieved from Radar/Lidar/Radiometer Measurements During ARESE and SUCCESS

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Introduction

Knowledge of the vertical structure of a cloud's microphysical characteristics is important for a variety of reasons. The vertical profile of cloud droplet size and liquid water content (LWC) affects the cloud's interaction with radiation and the determination of effective radius (re) from passive satellite measurements. Modeling the processes producing and maintaining clouds can be verified or improved with accurate measurements of the cloud's microphysical morphology. Traditionally, in situ aircraft measurements have been necessary to obtain such vertical profiles. With the availability of cloud radars and other measurement systems, it is now possible to remotely sense the vertical structure of cloud droplet size and LWC from the surface as the clouds advect overhead. More data sets have been processed during both U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE) and the National Aeronautical and Space Administration (NASA) Subsonic Clouds and Contrails Effects Special Study (SUCCESS) experiments, but this paper will focus on data taken from ground-based instruments at the ARM Program's Southern Great Plains (SGP) Central Facility during April 14, 1996, when a continental boundary-layer stratus cloud was present all day.

Data and Methods

The ground-based measurements used in this study are the Pennsylvania State University 94-GHz cloud radar reflectivities (Clothiaux et al. 1995), laser ceilometer measurements of cloud base, and microwave radiometer measurements of cloud liquid water path (LWP). The broadband shortwave radiometers at the SGP site are also used for comparison. However, the retrievals described here do not require solar flux measurements and, consequently, can also be applied to data obtained during the night.

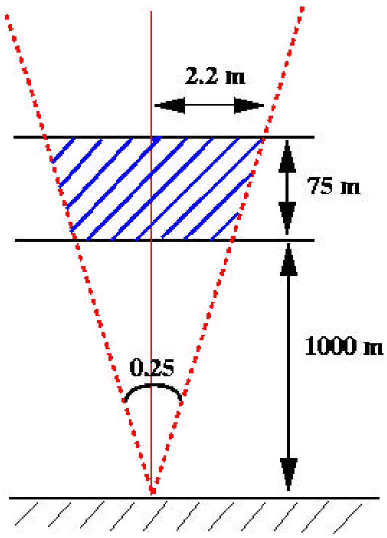
The capability of a radar to detect cloud particles depends, in part, on the concentration of droplets throughout the radar sample volume (see Figure 1), the cloud liquid or ice water content, the radar wavelength, and the sensitivity of the radar. For example, as the operating wavelength of a millimeter-wavelength radar decreases, its sensitivity to small particles increases because of the inverse dependence of cloud-particle backscatter cross-sections on radar wavelength. However, as the radar wavelength decreases, the cost of radar components increases and atmospheric attenuation as a result of water vapor and oxygen increases. Although the current analysis uses data from a 94-GHz cloud radar, data can also be used from the ARM 35-GHz millimeter-wavelength cloud radar (MMCR) (e.g., Clothiaux et al. 1998), which started operation in November 1996.

Three techniques for inferring vertical profiles of LWC and re were applied to the April 14, 1996, dataset. The first technique (M1) uses the radar reflectivity alone. Data from the ground up to 500 m are not used because of clutter contamination. The equations for this approach are

$$LWC_1(z) = 0.302 \rho_W N Z(z), \qquad (1)$$

and

How many cloud droplets in a Radar column?



At 1 km, the radar volume for a beamwidth of 0.25 degrees and a 75 meter pulse-length comprises:

(1) Radius R = 2.2 m

(2) Area S = 15 m^2

(3) Volume V = 1125 m^3

(4) If assumed LWC = 0.3 gm^{-3}, and r = 10 μm in that column, then the number concentration is
$N = 7.2 \times 10^7\ m^{-3}$

(5) The total number of cloud droplets in that column is
$N_t = 8 \times 10^{10}$

(6) In a 5-minute period, and radar beamed every 6 seconds, the total number of cloud droplets is
$N_{tt} = 4 \times 10^{12}$

Conclusion: The retrieved LWC and re profiles represent the averaged values in each column (~10^{12} cloud droplets).

Figure 1. About 10^{12} cloud droplets in a radar sample column in a 5-min. time resolution. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong-98.pdf*.)

$$Z(z) = 2^6 N\langle r^6 \rangle = 2^6 N\langle r_{el}(z)\rangle^6 \exp(3\sigma\chi^2), \qquad (2)$$

where σ_X(= 0.35) = the logarithmic width of the particle size distribution

N (=257 cm^{-3}) = the averaged cloud droplet number concentration from 1800 UTC to 2300 UTC obtained from the 2-stream radiative transfer model retrievals (Dong et al. 1997)

ρ_W = liquid water density.

The second method (M2), which is similar to the method described by Frisch et al. (1995), uses a combination of radar reflectivity, laser ceilometer cloud base height and microwave radiometer LWP measurements. The cloud base heights obtained from the laser ceilometer are used to filter out clutter and drizzle in the radar returns from below cloud base. The microwave radiometer-derived cloud LWPs are used as a constraint on the vertical sum of the derived cloud LWCs.

The equations of Method 2 are

$$LWC_2(z) = \frac{\frac{LWP}{\Delta H} Z(z)^{1/2}}{\sum Z(z)^{1/2}}, \qquad (3)$$

and

$$r_{e2} = 70.12 \left\langle \frac{LWC_2(z)}{N} \right\rangle^{1/3}, \qquad (4)$$

where ΔH (=75 m) is the vertical extent of the radar sample volume and $[\sum Z(z)^{1/2}]$ represents the integrated radar reflectivity through the vertical extent of the cloud. Thus, the retrieved profile has a resolution of 75 m.

The third method (M3) is the same as Method 2 except the cloud droplet number concentrations (N) are varied with time, instead of a mean value as in Eq. (4).

Results and Discussion

Figure 2 shows the radar reflectivity measured at the ARM SGP Central Facility between 1800 UTC and 2300 UTC, April 14, 1996. The cloud varies in thickness from 600 m to 1000 m. The retrieved vertical profiles of LWC and re are illustrated in Figures 3 and 4 for Methods 1 and 2, respectively. The LWC from M1 is as great as 0.15 gm^{-3}, while re is no larger than 5.5 µm. The contours in Figure 3 closely mimic the basic radar returns in Figure 2. For example, the vertical features of both re and LWC at 2230 UTC are much like those in Figure 2. Such similarities are expected given the total reliance of M1 on the radar reflectivity. With the use of auxiliary data, M2 yields much larger values for both variables. The maximum LWC is boosted by a factor of 6 and occurs at both 1930 UTC and 2230 UTC. The re increases by a factor of 2 or more relative to that from M1. The features so prominent in Figure 2 are also less distinct in Figure 4 than in Figure 3 because the retrievals are not as closely coupled to the radar return. The mean cloud droplet number concentration (N=257 cm^{-3}) as shown in Figure 5 is used in both M1 and M2. M2 would be a good method to estimate cloud microphysical properties if the cloud droplet number concentration did not change too much. In reality, however, it varies a lot. Figure 5 shows that the column-mean cloud droplet number concentrations vary with time, and drop to about 150 cm^{-3} from about 400 cm^{-3} at 2020 UTC. This big drop leads to the retrieved re from M3 slightly smaller than those from M2 before 2020 UTC, and larger than those from M2 after 2020 UTC as shown in Figure 5.

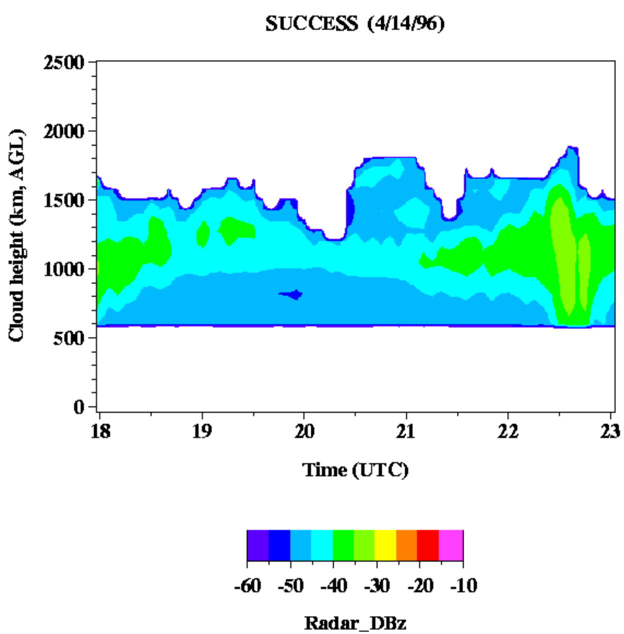


Figure 2. Radar reflectivity measured by Pennsylvania State University 94-GHz cloud radar during the SUCCESS experiment on April 14, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong-98.pdf*.)

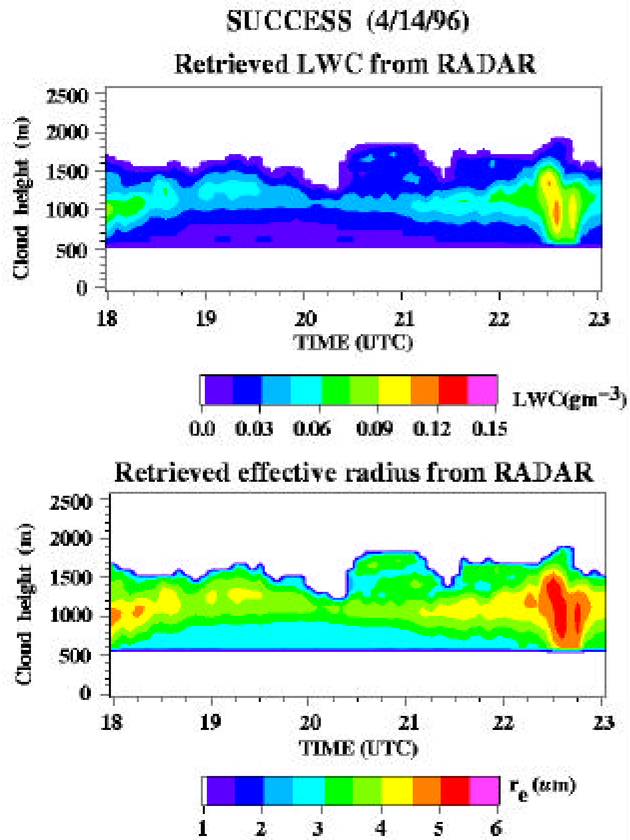


Figure 3. Method 1 (M1): Vertical profiles of cloud LWC and re retrieved from radar reflectivity during the SUCCESS experiment on April 14, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong-98.pdf*.)

The integration of re yields a value that can be compared directly to re derived from passive remote sensors on the ground or above the cloud. Such comparisons provide an independent evaluation of the radar-derived property. Figure 6 compares the column-mean values of re derived from the three methods with re retrieved from a 2-stream radiative transfer model constrained to match the surface shortwave radiometer measurements (Dong et al. 1997). Both the LWC and re from M2 and M3 show good agreement with those from the 2-stream model, while the magnitudes of the values derived from M1 are much lower than the values derived from the 2-stream model.

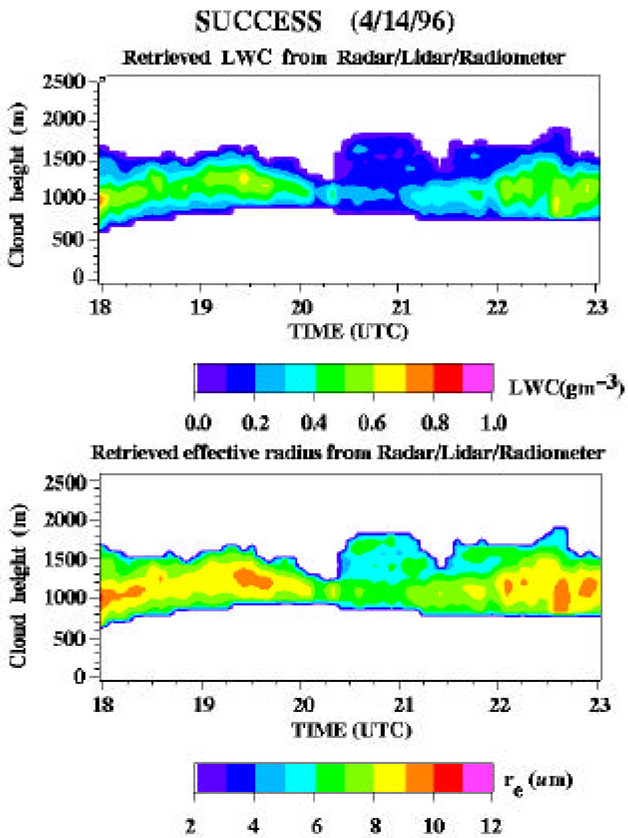


Figure 4. M2: Vertical profiles of cloud LWC and re retrieved from the combination of radar reflectivity, laser ceilometer (cloud base) and microwave radiometer (LWP) measurements during the SUCCESS experiment on April 14, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong-98.pdf*.)

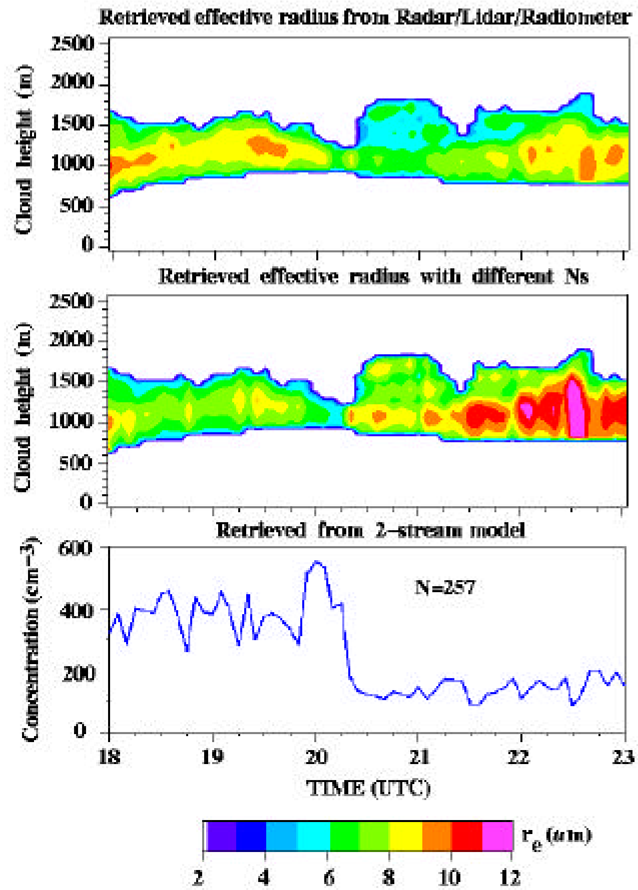


Figure 5. M3: Same as M2, but with time series of cloud droplet number concentration inputs. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong-98.pdf*.)

These results clearly demonstrate that cloud property retrievals using only radar reflectivity data are quite limited by radar calibration issues, while combining the radar reflectivities with ceilometer and radiometer measurements show much more promise as a reliable cloud property retrieval technique. Initial validation of this latter approach using in situ aircraft data is given by Dong et al. (1998). Additional study of this multi-instrument approach will permit routine quantification of cloud microphysical structures over the ARM sites with subsequent development of statistical databases for cloud modeling and satellite validation.

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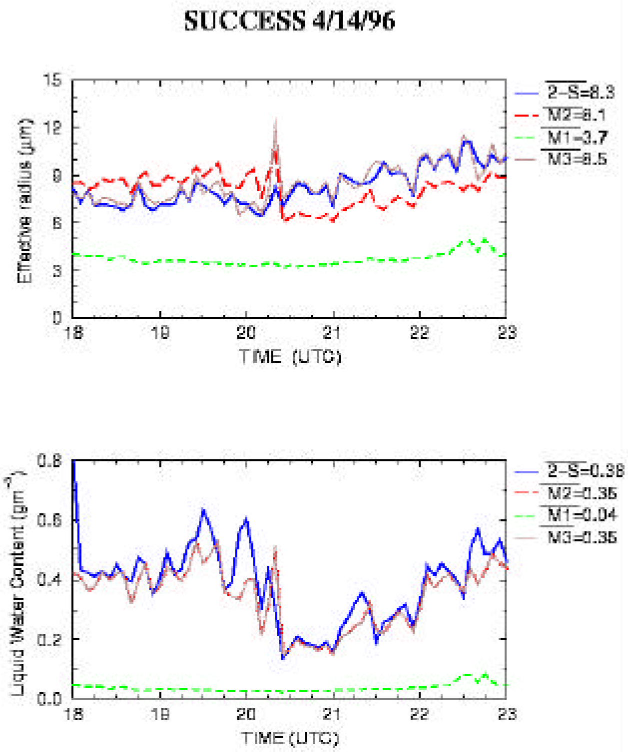

Figure 6. The column-mean values of LWC and re of three methods compare to those retrieved from the 2-stream radiative transfer model. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong-98.pdf*.)

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