Validation of Cloud Microphysical Retrievals from Surface- and Satellite-Based Measurements Obtained During the Fall of 96 Penn State Aircraft Experiment

X. Dong
Analytical Services and Materials, Inc.,
Hampton, Virginia

E. E. Clothiaux, N. Miles, J. Verlinde, and T. P. Ackerman
The Pennsylvania State University
University Park, Pennsylvania

P. Minnis
NASA-Langley Research Center
Hampton, Virginia

B. A. Albrecht
University of Miami
Miami, Florida

Introduction

Comparisons with aircraft in situ measurements are critically needed to quantify the uncertainties in Atmospheric Radiation Measurement (ARM) surface-and satellite-band retrievals of cloud properties. During the fall of 1996, measurements were made from a ground-based remote sensing site in central Pennsylvania in conjunction with University of Wyoming King Air aircraft flights over the area. The goal of this experiment was to validate ground- and satellite-based retrievals of cloud droplet effective radius, number concentration, and cloud liquid water content (LWC) using in situ aircraft measurements. This paper reports the results of one case study of an extended continental stratus cloud that was intensively sampled and observed by the aircraft and ground-based remote sensors and aircraft in situ instruments during the experiment on October 24, 1996. The comparison of these results provides more data for assessing the uncertainties in the remotely sensed parameters over the ARM sites.

Data and Methods

The ground-based remote sensing system consisted of a multichannel microwave radiometer, a 94-GHz cloud radar, a laser ceilometer, and an Eppley precision spectral pyranometer (PSP). These instruments are used to derive cloud liquid water path (LWP), cloud top height, cloud base height, and downward solar flux at the surface, respectively. Conventional radiosondes were also launched to provide vertical temperature, pressure, and relative humidity profiles. All of the measurements are used in a 2-stream radiative transfer model (Dong et al. 1997) to retrieve cloud droplet effective radius and number concentration. The cloud LWC is calculated as the ratio of LWP to cloud thickness. The column-mean cloud droplet effective radius (re) and LWC are also retrieved from combined measurements of radar reflectivity, laser ceilometer cloud base height and microwave radiometer LWP (Dong et al. 1998). The Geostationary Operational Environmental Satellite (GOES-8) data were also collected each half-hour at a 4-km resolution. The cloud optical depth (τ) and re are retrieved by matching the observed visible reflectance (0.65 μm) and near-infrared reflectance (3.9 μm) to the adding-doubling radiative transfer model calculations (Minnis et al. 1995; Minnis et al. 1998). Average values were computed for a 30-km square box over the surface site. The cloud LWP is proportional to the product of τ and re (Minnis et al. 1995).

Probes on the research aircraft provided in situ measurements of the cloud microphysical properties. Cloud droplet spectra were measured with a Forward Scattering Spectrometer Probe (FSSP) built by Particle Measuring Systems, Inc. The FSSP sized and counted individual particles in 15 2-μm wide bins; the bin centers ranged from 2 μm to 30 μm. Coincidence and dead-time corrections were applied to the FSSP measurements (Baumgardner et al. 1985). Cloud LWC and cloud droplet number concentrations N were calculated from each FSSP spectrum. The cloud droplet re was computed as the ratio of the third to the second moment of the cloud particle size spectrum.

Results

Rock Springs (44.72°N, 77.9°W) is located in central Pennsylvania approximately 10 km west of State College, where the Department of Meteorology of The Pennsylvania State University operates an experimental field site. Figure 1 shows GOES-8 visible images hourly over central Pennsylvania (the red spot is the surface site) with the range of 150-km east-west and 220 km north-south on October 24, 1996. The cloud moved from west to east at the typical boundary-layer cloud speed of 11 m/s. Local noon is ~17:00 UTC. The cloud was solid in the morning and became scattered and broken during the afternoon, finally dissipating around 19:30 UTC. The cloud base and top

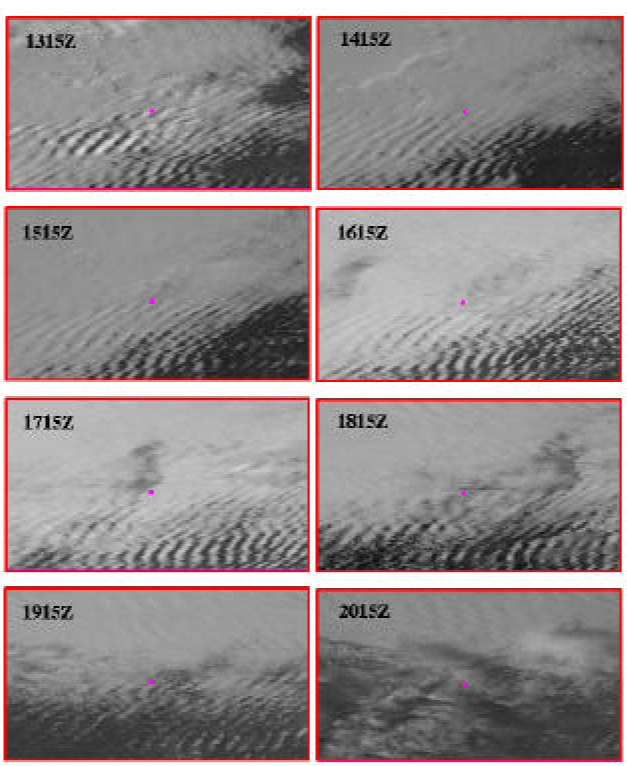

Figure 1. GOES-8 visible images hourly over the surface site (the red spot), Rock Springs (44.72°N, 77.9°W), central Pennsylvania in the range of 150 km east-west and 220 km north-south on Oct. 24, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(2)-98.pdf*.)

heights are 1 km and 1.5 km, respectively (Figure 2). Cloud LWP shows a strong negative correlation with downward solar flux (Figure 2). The vertical profiles of temperature, dew point and relative humidity in Figure 3 suggest the existence of a cloud with the same boundaries as those measured by the 94-GHz cloud radar and laser ceilometer. Because the cloud temperatures are greater than 0°C, it can be safely assumed that no ice was present in the cloud.

The two aircraft flights during October 24, 1996 (Figure 4), took place from 12:30 UTC to 16:18 UTC and from 18:10 UTC to 19:30 UTC. The long leg of the flight pattern was oriented parallel to the prevailing wind and the racetrack was to the north of the ground-based site since more cloud

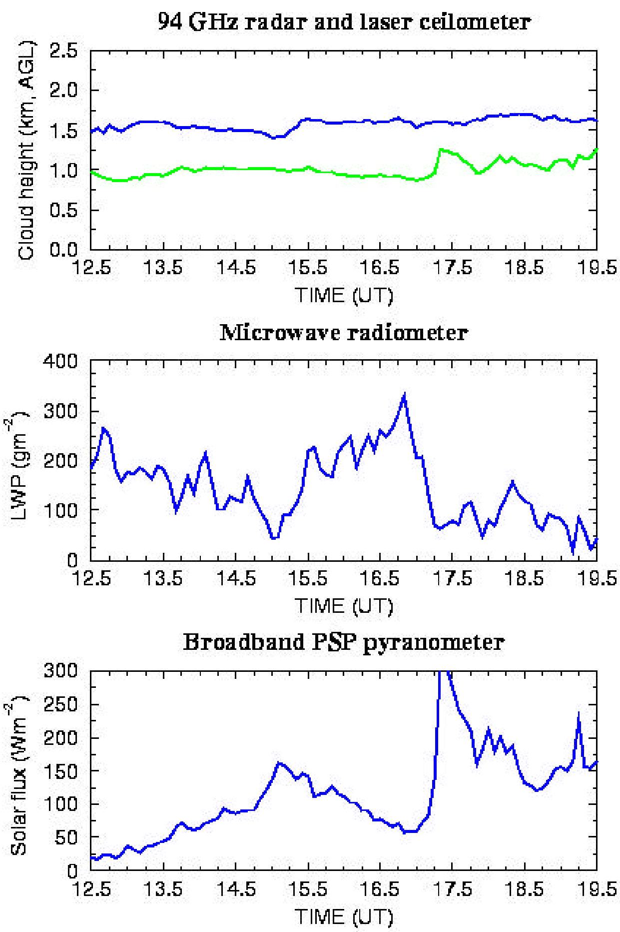

Figure 2. The ground-based measurements, including cloud top and base from a 94-GHz cloud radar and laser ceilometer, respectively, cloud LWP from microwave radiometer and downward solar flux from an Eppley PSP pyranometer on October 24, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(2)-98.pdf*.)

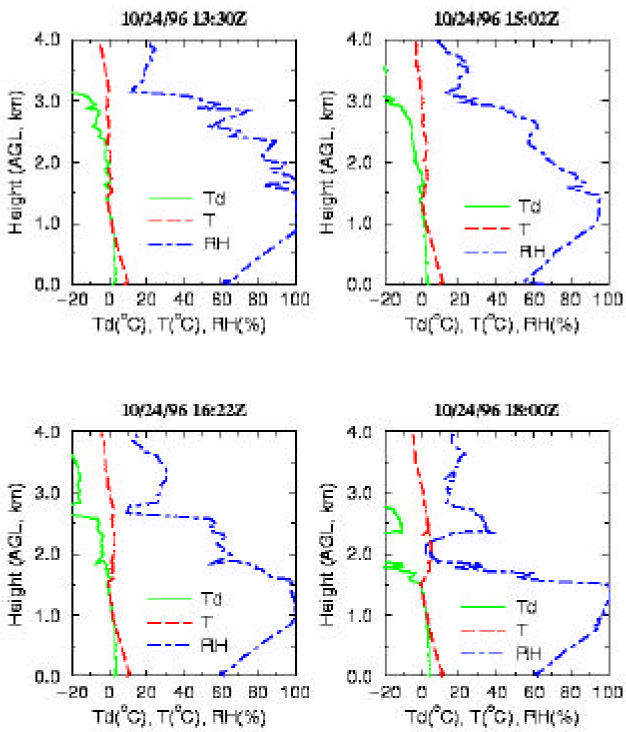

Figure 3. Vertical profiles of temperature, dew point and relative humidity from conventional radiosondes in every 1.5 hours on October 24, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/ conf_9803/dong(2)-98.pdf*.)

was located in this region. The vertical location of the aircraft relative to the cloud boundaries is illustrated in Figure 5a. During the first flight, the aircraft spent the majority of the time near cloud top, whereas during the later flight, the aircraft slowly spiraled up and down through the cloud. The values of re, N, and LWC derived from the FSSP spectra are plotted in Figure 5 with the same quantities derived from both the 2-stream and radar/ lidar/radiometer retrievals. Given the considerable differences in their origin, the good comparison between the three datasets is quite remarkable. The aircraft speed was about 90 m/s. The FSSP has a depth of field of about 3 mm and a beam diameter of 0.2 mm, giving a sample cross section of about 6 x 10^{-7} m^2 (Baumgardner 1983). Thus, in 5 minutes, the airplane travels 27 km (about one racetrack in Figure 4) and the FSSP samples about 0.016 m^3 of air. Because the aircraft was mostly flying at constant altitude, we can view each aircraft data point in Figure 5 as a snapshot in time along a very thin horizontal line at a single level in the cloud. If the cloud cells scale with the boundary layer height of approximately 1.5 km, then each data point represents an average across perhaps 15 cells with updrafts

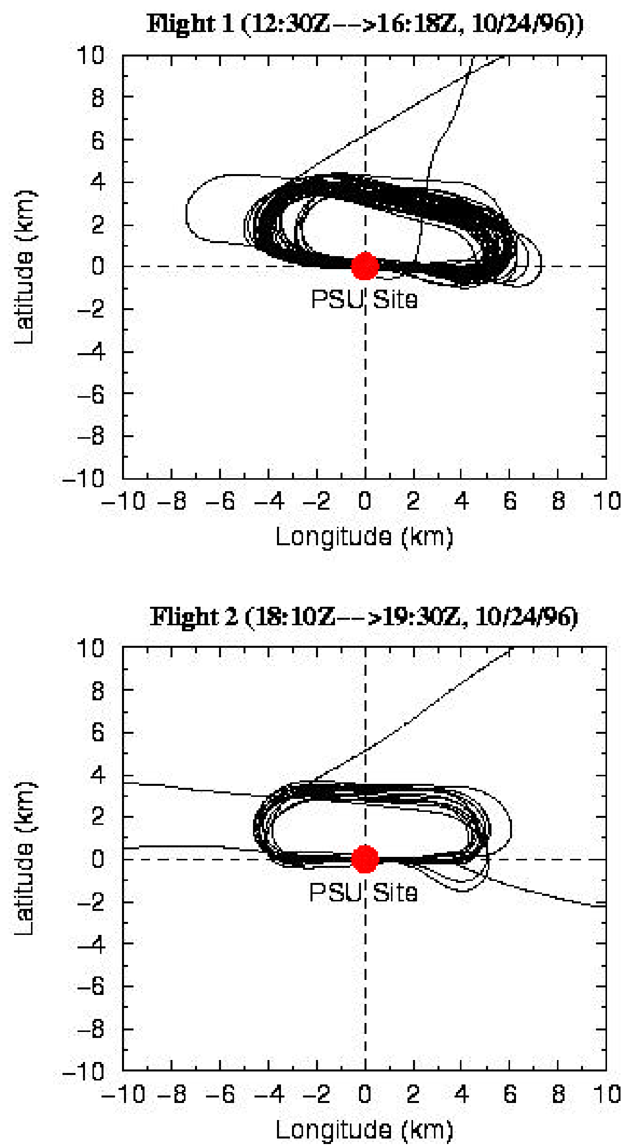

Figure 4. University of Wyoming King Air aircraft flight patterns over the surface site during the October 24, 1996. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(2)-98.pdf*.)

(12:30 UTC to 14:30 UTC), re decreased and N increased and downdrafts. During the early part of the record (12:30 UTC to 14:30 UTC), re decreased and N increased relatively smoothly, indicating that the spatially averaged microphysical characteristics were changing with time.

The surface retrieval techniques use data from a cylinder of cloud directly above the ground-based instruments. The microwave radiometer has a nominal field of view of

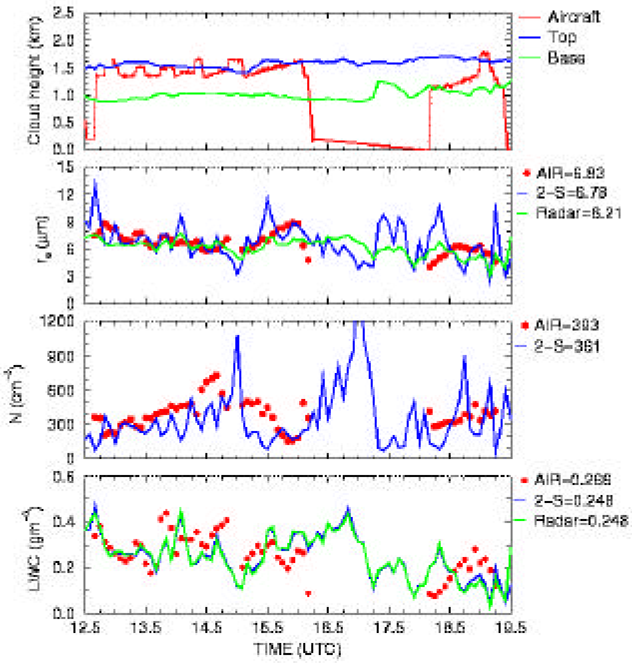

Figure 5. Aircraft altitude during the two flights are illustrated in (a). The retrieved and in situ measured cloud droplet effective radii (re), cloud droplet number concentration (N) and cloud LWC at 5-min. temporal resolution are illustrated in (b), (c) and (d), respectively. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/ conf_9803/dong(2)-98.pdf*.)

5 degrees. At 1.25 km, this translates into a horizontal diameter of 110 m. For a cloud with a thickness of 500 m, the instantaneous sample volume for the microwave radiometer is 10^7 m^3. The solar radiation measurement samples an even larger volume because of its hemispheric field of view. The individual retrieval points in Figure 5 each represent the vertically averaged microphysics at a given time. For a wind speed of 10 m/s, the cloud field will advect about 3 km, or about 2 cell sizes, each 5-minute interval. Thus, one interpretation of the point-to-point variability in the retrieved values is that it represents real variability between adjacent cloud columns. Some component of the variability, however, may be introduced by the assumption of plane-parallel radiative transfer. During periods of relatively high transmission, such as when the solar direct beam penetrates a gap in the cloud, the retrieval solution tends toward larger and fewer droplets in order to match the transmission with a fixed amount of liquid water. Although these two effects are difficult to differentiate, it is likely that some of the variability is real. The retrieved microphysical values show the same trend of decreasing re and increasing N as observed in the aircraft data. The three data streams also show a similar pattern of variability in LWC.

It is often assumed that spatial and temporal statistics are essentially interchangeable, which is the so-called ergodic approximation. The 5-min. averaging periods in Figure 5 are too short to test this approximation given the huge mismatch in sample volumes. Therefore, 5-min. data were averaged to a temporal resolution of 30 min., which also matches the GOES-8 retrievals (Figure 6). In Figure 6, the red-filled circles represent the 30-min. averaged aircraft data, the blue circles are the 2-stream model results, the green squares are from the combined measurements of radar/lidar/radiometer, and the brown diamonds correspond to the GOES-8 analyses. The agreement between the aircraft and surface-retrieved 30-min. averages is extremely encouraging. It suggests that both the aircraft and ground-based data are capable of characterizing the cloud microphysics on this time scale, assuming that the common values to which these data converge represent the actual microphysical structure of the cloud. This good agreement also implies either that much of the point-to-point variability

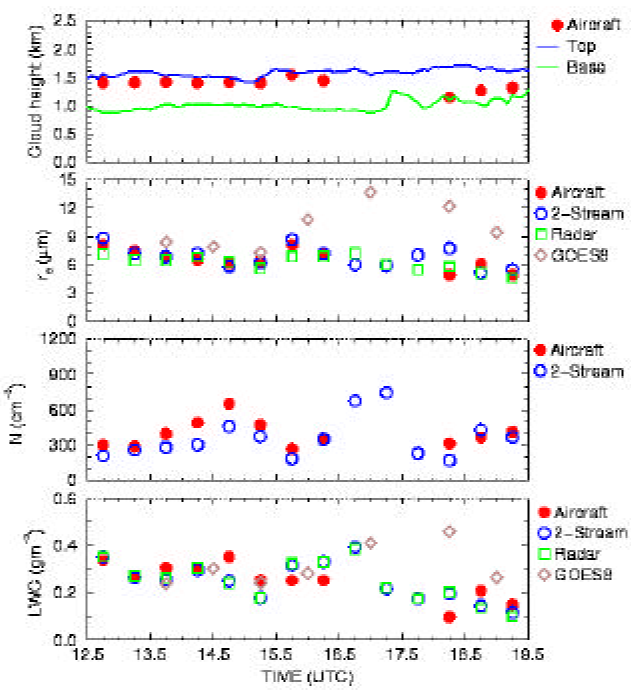

Figure 6. Same as Figure 5, but with 30-min. temporal resolution and including GOES-8 retrievals. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_98 03/dong(2)-98.pdf*.)

seen in the 5-min. retrieval values is real, since it averages to comparable values derived from the aircraft, or that the retrievals averaged over 30-min. intervals are relatively insensitive to the effects of cloud inhomogeneities. Both data sets show the trends identified earlier from 12:30 UTC to 14:30 UTC. The agreement is not as close during the second flight, which may be due to the aircraft sampling strategy (the spiral) not providing an adequate spatial sample or to the short duration of the flight. Despite the relatively few points in the 30-min. data series, the linear correlation coefficients for the three cloud properties ranged from 0.63 to 0.73.

There is good agreement between the surface and aircraft datasets and the GOES-8 retrievals during the morning (Figure 6). The re from GOES-8 have the same trend as, but are slightly larger than, those from surface and aircraft in the morning. This small difference arises for several reasons. The GOES-8 spatial sampling and retrieval technique is different than those for either the surface or aircraft. The satellite retrieval may be more representative of the conditions at cloud top because of the nature of the attenuation of the 3.9-μm radiance. An overestimation of the 3.9-μm channel solar constant would also yield an overestimate of re. The good agreement during the morning is also evident in the plot of LWC in Figure 6. However, the GOES-retrieved re and LWC are much greater than those from the surface and aircraft during the afternoon. These discrepancies may be due to interpolation errors in the reflectance models used in the satellite retrieval or to ice-cloud contamination. The variation in reflectance with sun-scene-satellite geometry, which is greatest in the back-scattering direction, may not be entirely captured by the spacing of the node points in the reflectance models (Minnis et al. 1998) leading to errors in the retrieved values at particular angles. The scattering configuration was closest to backscattering at 17:00 UTC when the differences were the greatest. Also, some thin cirrus clouds were evident in the GOES infrared imagery around the surface site during the afternoon. These thin, high ice clouds were not detected by the surface instruments and cannot be seen in the GOES-8 visible images in Figure 1. A thin cirrus cloud would reduce the 3.9-μm radiance resulting in an overestimate of re and LWC relative to those from the surface and aircraft data. While it is essential that such effects are understood, the overall impact of cirrus-contaminated scenes on the uncertainties in the satellite retrievals should be quantified because they will be encountered in any operational satellite retrieval application.

Summary

The aircraft data and ground retrievals averaged over 5-min. intervals are similar in trend and magnitude. The remotely sensed properties are substantially more variable, which may be due to the nature of the retrieval technique. But perhaps the retrievals indicate some actual variability in the properties of adjacent cloud columns. For 30-min. averages, the surface and aircraft data sets converged to remarkably similar values suggesting that both the aircraft and ground-based data are capable of characterizing the cloud microphysics on this time scale. This good agreement also implies either that much of the point-to-point variability in the 5-min. retrievals is real or that the effects of cloud inhomogeneities on the retrieval over a 30-min. interval are not very important. The retrievals from GOES-8 agree well with the 30-min. averages of surface and aircraft data without cirrus cloud contamination.

Although this is only one case study, there are no prior cases that have sufficient aircraft, surface and satellite to derive all of these microphysical quantities intensively over the surface site for a 7-hour period. Duplication of this approach using data from other flight programs will greatly enhance the value and confidence of the surface-derived cloud properties. The almost continuous ARM measurement of the parameters used in the surface retrievals will provide for the sampling of a wide variety of cloud configurations over the long time periods necessary for quantifying the uncertainties in the satellite-derived cloud properties.

References

Baumgardner, D., 1983: An analysis and comparison of five water droplet measuring instruments. *J. Clim. Appl. Meteorol.*, **22**, 891-910.

Baumgardner, D., W. Strapp, and J. E. Dye, 1985: Evaluation of the forward scattering spectrometer probe. Part II: Corrections for coincidence and dead-time losses. *J. Atmos. Oceanic Technol.*, **2**, 626-632.

Dong, X., T. P. Ackerman, E. E. Clothiaux, P. Pilewskie, and Y. Han, 1997: Microphysical and radiative properties of boundary layer stratiform clouds deduced from ground-based measurements. *J. Geophys. Res.*, **102**, 23,829-23,843.

Dong, X., E. E. Clothiaux, P. Minnis, and T. P. Ackerman, 1998: Vertical profiles of continental stratus cloud properties retrieved from radar/lidar/radiometer measurements during ARESE and SUCCESS. This proceedings.

Minnis, P., D. P. Kratz, J. A. Coakley, Jr., M. D. King, R. Arduini, D. P. Garber, P. W. Heck, S. Mayor, W. L. Smith, Jr., and D. F. Young, 1995: Cloud optical property retrieval (Subsystem 4.3). "Clouds and the Earth's radiant energy system (CERES) algorithm theoretical basis document, Volume III: Cloud analyses and radiance inversions (subsystem 4)." NASA RP 1376 Vol. 3, edited by CERES Science Team, December, 135-176.

Minnis, P., D. P. Garber, D. F. Young, R. F. Arduini, and Y. Takano, 1998: Parameterizations of reflectance and effective emittance for satellite remote sensing of cloud properties. *J. Atmos. Sci*., in press.