# Comparison of Stratus Cloud Optical Depths Retrieved from Surface and GOES Measurements over the ARM SGP Central Facility

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## Introduction

The climatic importance of the microphysical and radiative properties of clouds, particularly cloud droplet effective radii ($r_e$), optical depths ($\tau$), and albedos are widely recognized. For reliable application of satellite datasets in cloud process and single column models, it is important to have a reasonable estimate of the errors in the derived cloud properties. When properly used, ground-based instruments can provide a cloud truth dataset for estimating errors in the satellite products. Because clouds are so variable, a statistically reliable validation requires coincident satellite-surface measurements taken in a variety of conditions. This paper examines the retrievals of boundary-layer stratus cloud properties and associated top-of-atmosphere (TOA) albedos.

## Data

Data derived from Geostationary Operational Environmental Satellite (GOES) radiances taken during the 1994 Atmospheric Radiation Measurement (ARM) Spring Intensive Observation Period (IOP), Fall 1995 ARM Enhanced Shortwave Experiment (ARESE), and 1996 Spring IOP are compared here with ground-based measurements. These include cloud liquid water path (LWP) from the ARM microwave radiometer, cloud base and top from the laser ceilometer and radar, respectively, downward solar flux ($F_s$) from an Eppley precision spectral pyranometer (PSP), and soundings from radiosondes. All of the measurements were used in a $\delta$2-stream radiative transfer model (Dong et al. 1997) to retrieve cloud droplet effective radius ($r_e$), optical depth ($\tau$), and cloud and TOA broadband albedos ($R_{cld}$, $R_{toa}$), respectively. These ground-based measurements and retrievals are compared to similar quantities derived from the Geostationary Operational Environmental Satellite (GOES)-7 (Minnis et al. 1995 and updates) and GOES-8 (Minnis and Smith, Jr. 1998) measurements over the ARM SGP central facility (SCF) at 36.61N, 97.49W. After sufficient testing against in situ data, ground-based retrievals in a number of climate regimes can be used to validate the satellite-based retrievals, which can ultimately provide a global database of cloud microphysical and radiative properties.

## Methods

The retrieval scheme uses the $\delta$2-stream radiative transfer model to compute the transmitted and reflected broadband shortwave fluxes over a range of $r_e$ and LWP as shown in Figure 1. Although $r_e$ and $\tau$ give rise to $F_s$ and LWP, the latter are measured directly so the retrieved parameters are shown as dependent variables. The left column of Figure 1 shows the relationships between $r_e$, $\tau$ and $R_{cld}$ for a range of LWP, $F_s$, and $r_e$ for a fixed cosine of solar zenith angle $\mu 0$. Effective radius increases linearly and $\tau$ grows monotonically with $F_s$ and LWP, while $r_e$ increases and $\tau$ decreases with increasing $F_s$. Conversely, cloud albedo increases with decreasing $r_e$ for constant LWP. The dependence of these parameters on $\mu 0$ for a constant $F_s$ are shown in the right column of Figure 1. For constant LWP, a larger effective radius leads to more forward scattering and fewer scattering events resulting in greater solar transmission for a given $\mu 0$. The cloud droplet effective radius has a much larger impact on the cloud albedo than $\mu 0$, as shown at the bottom of Figure 1. For example, for LWP = 200 $gm^{-2}$, cloud albedo drops by approximately 30% as $r_e$ increases from 4 $\mu m$ to 20 $\mu m$ (left), while cloud albedo decreases by only 10% as $\mu 0$ increases from 0.5 to 0.9 (right).

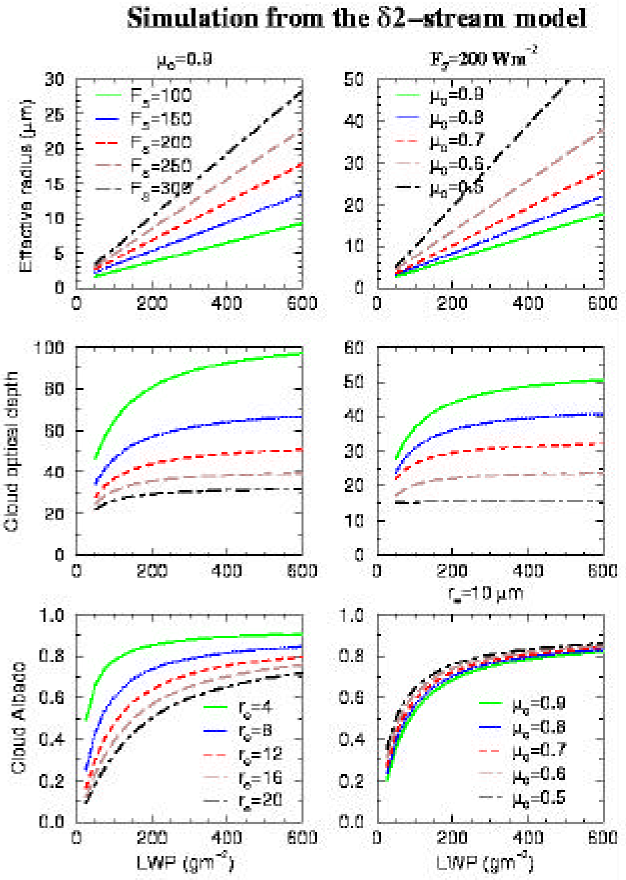

**Figure 1**. Cloud droplet effective radius, optical depth, albedo and TOA albedo, simulated from the δ2-stream radiative transfer model for a variety of cloud liquid water paths, downward solar flux and the solar zenith angles. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

TOA albedos and τ were also derived from half-hourly GOES 4-km visible data, then averaged over a 0.3° x 0.3° box centered on the SCF. Cloud optical depth is derived using the layer bispectral threshold method (LBTM) that matches the observed pixel-level reflectance to a reflectance parameterization that assumes $r_e$ = 8 μm (Minnis et al. 1995). The TOA broadband albedo was computed from the GOES narrowband albedo using an empirical relationship based on a correlation between coincident October 1986 GOES-6 and Earth Radiation Budget Experiment (ERBE) satellite data (Minnis and Smith, Jr. 1998). The narrowband albedo is simply the observed visible reflectance corrected for anisotropy using a bidirectional reflectance model (Minnis et al. 1995).

# Results and Discussion

The TOA broadband albedos and τ from GOES are compared in Figures 2 through 8 with those deduced from the ground-based measurements. During April 1994 (Figures 2 and 3), the results from GOES-7 show excellent agreement with the surface retrievals and correspond closely to the LWP variation except for a couple of points in Figure 3. The cloud droplet effective radii deduced from the ground-based measurements vary little with mean values between 5 μm and 8 μm. The TOA albedos from GOES-8 are, on average, about 9.1% (or 16.5% relative to the mean

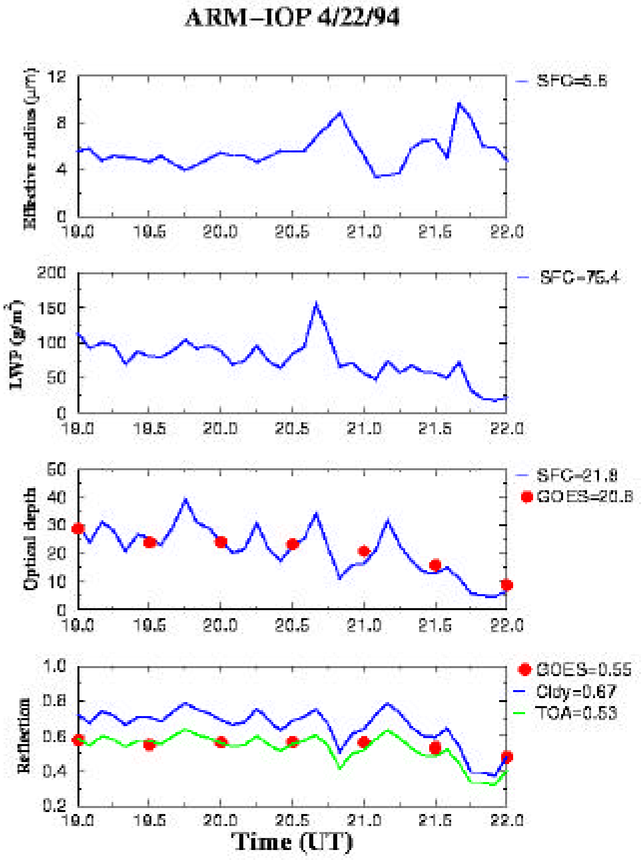

**Figure 2**. Cloud droplet effective radius, LWP, optical depth, albedo (solid blue) and TOA albedo (solid green) deduced from ground-based measurements, and from GOES-7 measurements (filled circle) on April 22, 1994 over the ARM SCF. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98. pdf*.)

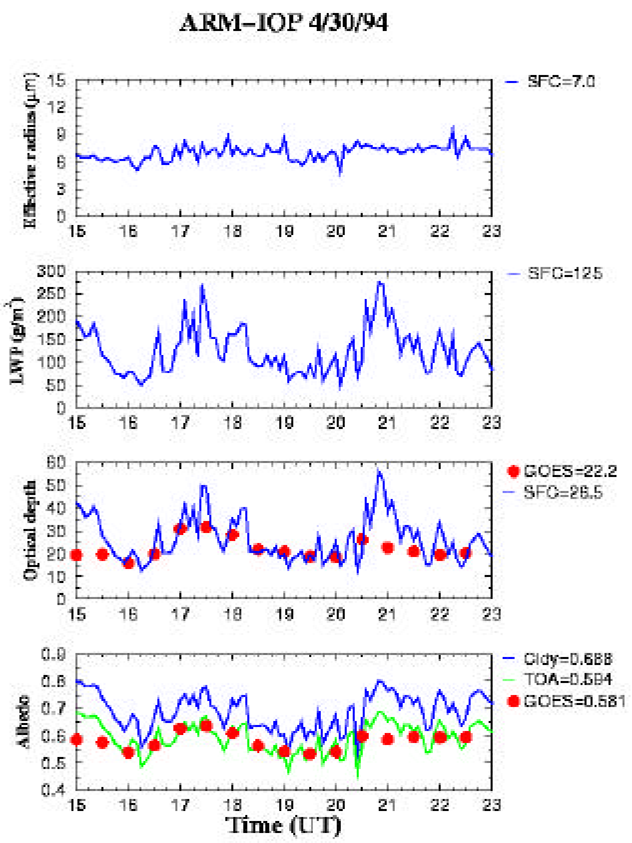

**Figure 3**. The same as Figure 2, but for April 30, 1994. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

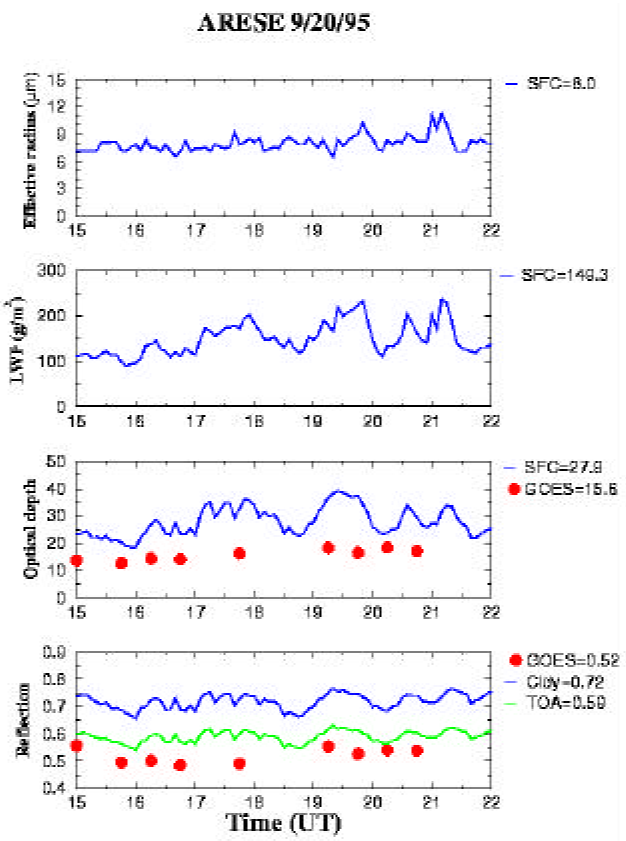

**Figure 4**. The same as Figure 2, but for GOES-8 and September 20, 1995 (ARESE). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

GOES-8 TOA albedo) less than those deduced from ground-based measurements for cloudy (Figures 4 through 6) and clear skies (Figure 7). The cloud optical depths from GOES-8 do not appear to be very sensitive to LWP and are only about half of those deduced from ground-based measurements. Scatterplots of the half-hourly averaged surface retrievals and the GOES-7 and GOES-8 data are given in Figure 8. The $r_e$ deduced from the ground-based measurements during ARESE and April 1996 range from 5 µm to 11 µm with the mean value about 7 µm to 8 µm. These retrieved effective radii are typical of continental boundary-layer stratiform clouds and would seem to be accurate because the technique has been partially validated by aircraft in situ measurements (Dong et al. 1998). If both microwave-radiometer-measured cloud LWP and GOES-8 derived $\tau$ were accurate, $r_e$ would be ~15 µm, a value typical of drizzling maritime stratiform clouds. The discrepancies require investigation.

There are several possible reasons for the differences:

1. The GOES-8 visible channel calibration: This calibration relies on NOAA-14 Advanced Very High Resolution Radiometer (AVHRR) data (Ayers et al. 1998) that are periodically calibrated against a stable desert scene in North Africa (Rao and Chen 1996). The GOES-8 visible channel gain is increasing linearly within ~ ±3% of a regressed trend line (Ayers et al. 1998). This month-to-month stability confirms the successful execution of the planned improvements in the new generation of GOES satellites. Prior to GOES-8, the GOES visible channel gain was manually adjusted resulting in somewhat erratic and significant changes. If there are any significant uncertainties in the GOES-8 calibration, they must be a bias in the gain. Subsequently, the National Oceanic and Atmospheric Administration (NOAA)-14 visible calibration would be in error by the same amount of bias because it serves as the GOES-8 reference. An underestimation of the

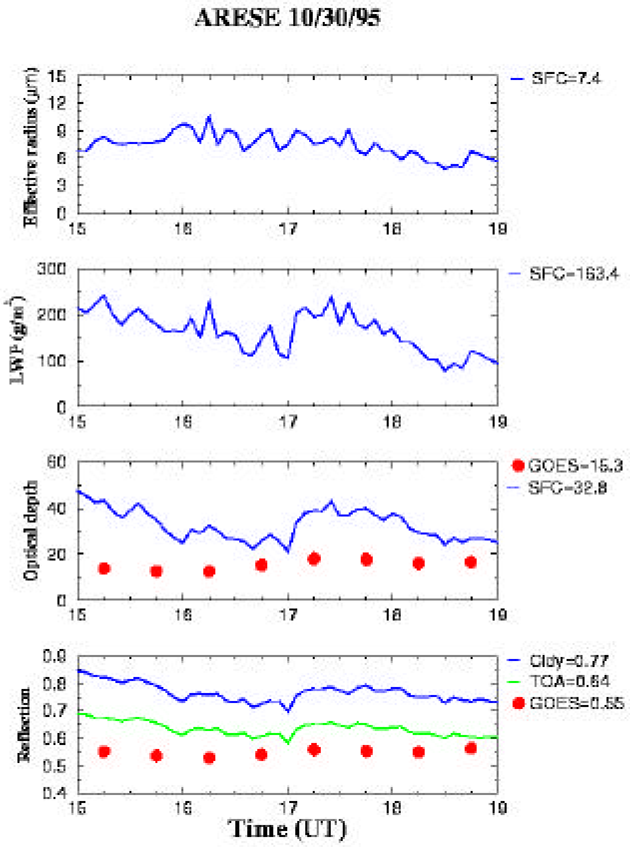

**Figure 5**. The same as Figure 2, but for GOES-8 and October 30, 1995 (ARESE). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

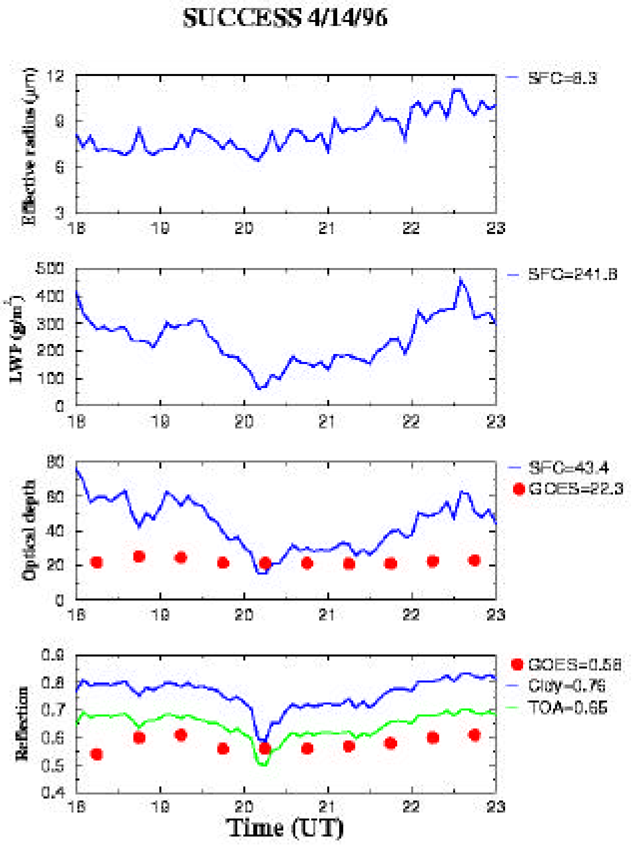

**Figure 6**. The same as Figure 2, but for GOES-8 and April 14, 1996 (SUCCESS). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

gain would result in albedos and optical depths smaller than those expected from the surface data. Given the good agreement between particle sizes and optical depths derived from surface, aircraft, and GOES-8 data over Pennsylvania for a continental stratus cloud and the stably increasing GOES-8 gain, it is difficult to assign the large discrepancies to the GOES-8 calibration.

2. The surface radiometer calibration: The surface retrievals depend on the Eppley PSP-measured downward solar flux. Significant differences in the observed and modeled clear-sky insolation for the ARESE time period have suggested some possible problems in the measurements, especially for diffuse radiation (Kato et al. 1997). All of the downwelling radiation at the surface is diffuse for these thick clouds. Underestimations of the insolation would result in underestimations of $r_e$ and overestimations of $\tau$. Thus, some additional examination of this potential effect is warranted.

3. View angles and different scales: The GOES-8 retrievals are based on bidirectional reflectance that must be corrected for anisotropy to obtain albedo. Comparisons between coincident GOES and Scanner for Radiation Budget (ScaRaB) data taken at a variety of angles and different scales yield a root mean square (rms) difference of 8% suggesting the anisotropic correction error is less than this value (Doelling et al. 1998). Spatial, temporal, and spectral differences also contribute to the error. A bias in albedo over the course of the day is inconsistent with the comparisons with other satellite data because the range of solar and viewing angles for GOES is similar in both surface and satellite comparisons. The surface data use advection to measure clouds over a spatial scale comparable to that of the satellite averages. The scale differences would induce random noise into the comparison rather than biases such as those seen here. The spatial-temporal trade-offs have been discussed in Dong et al. (1998).

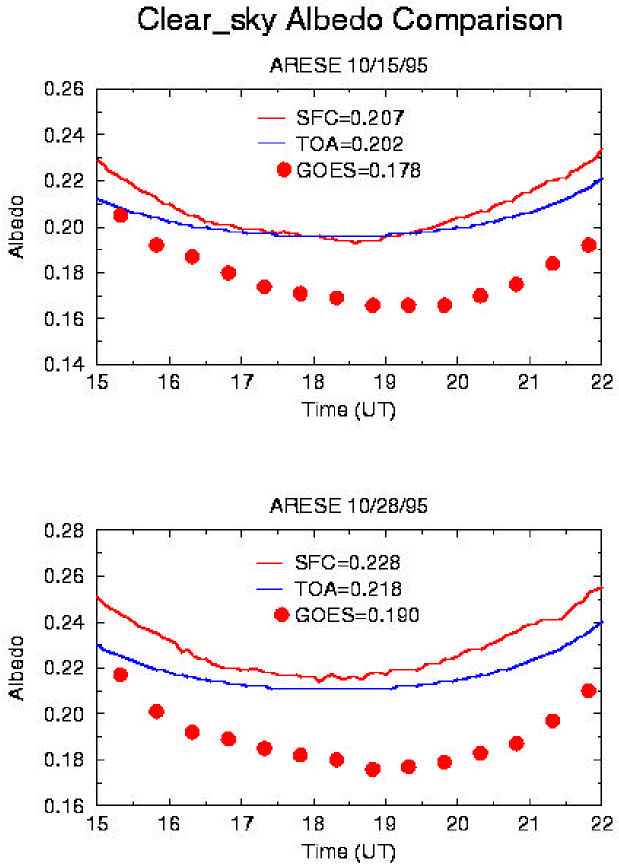

**Figure 7**. The shortwave surface albedo for clear sky derived from upward- and downward-pointing unshaded pyranometers at the ARM SFC during the ARESE experiment (red solid line), and TOA albedo calculated from the $\delta$2-stream model based on measured mean surface albedo and soundings (blue solid line) and inferred from GOES-8 image (red circle). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

4. The satellite narrowband-to-broadband conversion: The GOES data are converted to broadband albedos using a historical conversion function based on ERBE scanner data. If the visible channel gain were biased or the conversion function changed because of variations in the scene constituents, the GOES-8 albedo would be biased. Comparisons with ERBE WFOV data indicate that the GOES-8 albedos are, on average, 1% to 6% greater than the ERBE values with the largest difference occurring during ARESE. Comparisons with the ARESE Egrett broadband flux measurements show that the GOES albedos are somewhat larger than the TOA-adjusted aircraft albedos. Thus, it is unlikely that the biases in albedo are due to GOES-8, because the GOES-8 values are smaller than those inferred from the surface insolation.

5. The derived droplet sizes and LWP: The larger values of $r_e$ required to reduce the 2-stream model albedos to match the GOES-8 values suggest clouds that are typical of continental stratus and are, possibly, drizzling. Examination of the radar images for 9/20/95 reveal some drizzle reaching the ground at times during the day. Multilayer clouds occurred during 10/30/95. Drizzle is evident during much of the day, emanating from both upper and lower layers, often reaching the ground or lowest 500 m of the atmosphere. Thus, droplets larger than those found in non-precipitating stratus are expected during these 2 days. Radar images were unavailable during April 1994 prohibiting the evaluation of possible drizzle. The agreement between the two retrievals, however, suggests that drizzle is unlikely for that day. The 4/14/96 radar imagery reveals relatively weak returns from a layer that appears stable throughout most of the day. Therefore, a large value of $r_e$ is unlikely. The large values of LWP for this day appear unrealistic considering the stability of the layer, the relatively small $r_e$, and the relatively low GOES-8 albedos. While it is expected that LWP is accurately derived from the microwave data, a comprehensive validation of the ARM LWP data is needed to fully understand their quality. Additional retrievals of particle sizes from the GOES-8 data using multispectral methods may elucidate the impact of particle size on the derived optical depths.

6. Anomalous cloud shortwave absorption: If the clouds are absorbing more radiation than expected from the model calculations and all of the measurements are accurate, then the albedos computed from the insolation would be larger than observed and the particle sizes would be smaller. Using two stacked aircraft below and above the cloud, Valero et al. (1997) and Zender et al. (1997) found that the heavy cloud on 10/30/95 over the ARM SGP site absorbed 37% of the incoming solar flux compared to the model-calculated 24% (in total atmospheric column) from this study and Li et al. (1998). They concluded that this excess cloud absorption occurred not only at near-infrared but also in the visible spectrum. Charlock et al. (1998) came to a similar conclusion and pointed out that strongly absorbing aerosols are a potential factor in this apparent excess cloud absorption. If the visible absorption is added to the models and the measured solar transmission is used as a constraint in the model, then $R_{toa}$ calculated from the models will be close to that

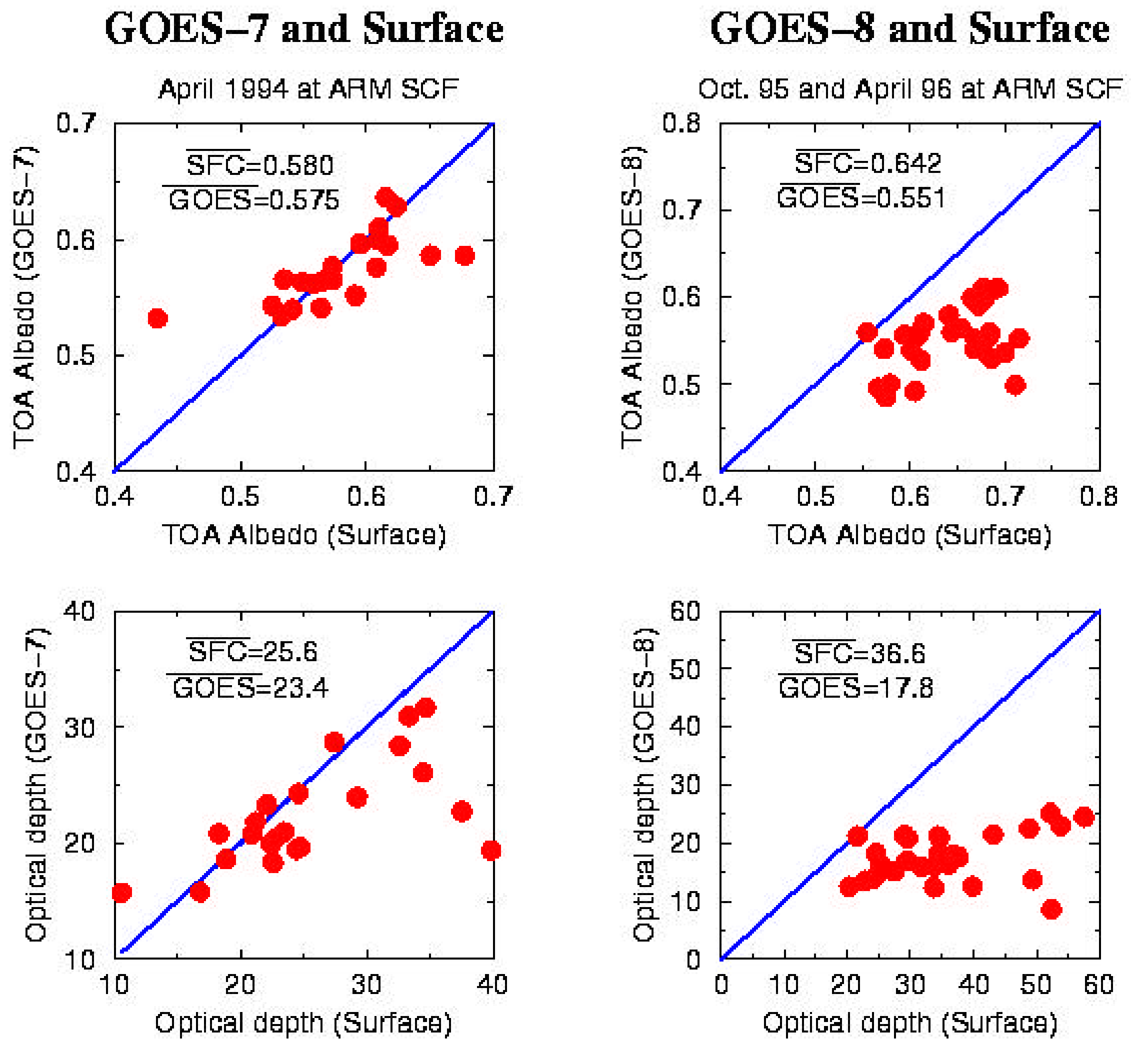

**Figure 8**. Comparison of half-hourly averaged surface retrievals with GOES-7 and GOES-8 retrievals. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/dong(3)-98.pdf*.)

inferred from GOES-8, cloud optical depth retrieved from GOES-8 will be much higher than current retrievals, and the newly retrieved optical depths will be close to those deduced from the ground-based measurements. However, Li et al. (1998) used the scanning spectral polarimeter (SSP) on the Egrett to derive $R_{toa}$ from reflected solar flux spectra. They found that the albedos inferred from SSP are about 14.4% larger than those from the Egrett Total Solar Broadband Radiometer (TSBR) and about 8.4% higher than those inferred from GOES-8. These results are consistent with the discrepancies found here.

While there are other possible sources for the discrepancies, those listed above are probably the most likely culprits. Fully understanding the differences in the retrieved quantities will require much additional investigation.

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