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Cloud properties derived from surface MFRSR measurements and comparison with GOES results at the ARM SGP site

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Abstract. We describe a family of inversion methods to infer the optical depth, τ, of warm clouds from surface measurements of spectral irradiance. Our most complex retrieval also uses the total liquid water path measured by a microwave radiometer to obtain the effective radius, r_e, of the cloud droplets. We apply these retrievals to data from the Atmospheric Radiation Measurement (ARM) Program, and compare our results to those produced by the GOES satellite for episodes where total overcast was observed. Our surface-based estimates of τ agree with those from GOES when the optical depths are <10, but are consistently larger by as much as a factor of 2 when optical depths are greater. We show that the uncertainties associated with the surface-based retrievals are less than those done from a satellite, and argue from the time series of the observations and the statistics of the measurements that the disagreement is not merely a consequence of the larger spatial average sampled by the satellite.

Surface Measurements

We use the following measurements taken at the ARM SGP site in Oklahoma (97.48° W, 36.61° N): spectral total-horizontal, diffuse-horizontal, and direct-normal irradiances at wavelengths of 415, 500, 610, 665, 862 and 940 nm (10 nm FWHM) measured every 15 seconds by a Multi-Filter Rotating Shadowband Radiometer (MFRSR) [*Harrison et al.*, 1994], and vertical liquid water path measured every 20 seconds by a zenith-viewing Radiometrics WVR-1100 Microwave Radiometer (MWR) operating at frequencies of 23.8 and 31.4 Ghz. As we describe below, the total liquid water path measured by the MWR allows us to independently retrieve r_e. This property is of direct interest for other purposes, but here our primary reason to do so is to improve the accuracy of our inferred optical depths. Microwave radiometers are far less common than MFRSR instruments; when total water-path measurements are unavailable inference of the optical depths must depend on an assumed value for r_e, as is done by the satellite retrievals.

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Inversion of Cloud Optical Depth and Droplet Effective Radius

We restrict our discussion to warm clouds only (those dominated by droplets). As is common, we parameterize the cloud droplet optics in terms of effective radius, r_e, and total liquid path, LWP. $r_e = \int n(r)r^3dr / \int n(r)r^2dr$ with $n(r)$ being the differential drop size distribution of the cloud.

Rawlins and Foot [1990] and *Hu and Stamnes* [1993] demonstrated that cloud-drop size distributions with equivalent r_e produce similar values for the single scattering albedo ω and the scattering asymmetry factor g. We use the Hu and Stamnes computations for ω and g as a functions of r_e and wavelength in our most complex retrieval below.

The delta-Eddington formulation of the radiative transfer can be solved analytically for a simple one cloud layer and a surface albedo A, and then used for inversion of cloud optical depths. It is less accurate than methods based on a forward model with a larger number of ordinates, but serves to demonstrate basic sensitivities of the inversion problem, and as a check on the more complex inversions. Figure (1) compares the logarithmic derivatives of transmittance and reflectance with respect to the cloud optical depths, computed from the delta-Eddington formulation. As the cloud optical depth increases the planetary albedo approaches an asymptotic limit; a satellite measuring the reflectance has rapidly decreasing sensitivity to distinguish among high optical depth cases. For optical depth beyond 15 the surface measurement of transmission is four to five times more accurate, given equal radiometric uncertainties. Other sensitivities are discussed in more detail later.

To improve the accuracy over that of the delta-Eddington formulation we employ an adjoint reformulation of the discrete ordinate radiative transfer method [*Min and Harrison*, 1996]. The discrete ordinate model [Stamnes et al., 1988] includes all orders of multiple scattering and is valid for vertically inhomogeneous, nonisothermal, plane-parallel media. The reformulation of this model into an adjoint problem preserves the method's generality, and improves computational efficiency for our operational inversion.

To obtain τ we need the observed atmospheric transmittance (rather than absolute irradiance), and the surface albedo. The MFRSR allows us to obtain both accurately without depending on absolute calibration because it measures both total-horizontal irradiance and direct-normal ir-

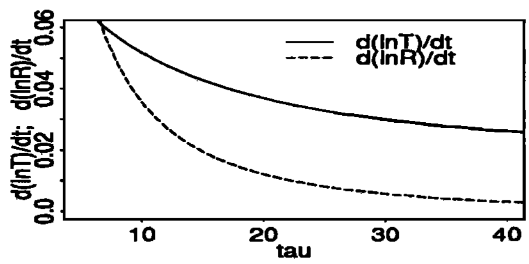

Figure 1. Sensitivities of transmittance and reflectance versus cloud optical depth, calculated from the delta-Eddington formulation for a solar zenith angle of 60°, $\omega = 0.99999$, $g = 0.866$.

radiance using the same detector(s) by a blocking technique. Consequently Langley regression of the direct-normal irradiance taken on clear stable days can be used to extrapolate the instrument's response to the top of the atmosphere [*Harrison and Michalsky*, 1994], and this calibration then applied to the total-horizontal irradiance. Transmittances can be calculated subsequently under cloudy conditions as the ratio of the uncalibrated output to the extrapolated top-of-the-atmosphere value.

The surface albedo can similarly be obtained from the direct-to-diffuse irradiance ratios available from the MFRSR on cloud-free days. We use the aerosol model from MODTRAN2 [*Berk et al.*, 1989] and simultaneously fit the aerosol optical depth and the surface albedo under such conditions. This inference of the surface albedo from upward-looking measurements depends on multiple scattering, and hence is most accurate for short wavelengths where the Rayleigh contribution is largest. Several other factors favor the 415 nm passband compared to those in the 500 to 700 nm range: when snow is absent terrestrial albedos at 415 nm are significantly lower, ω and g are less sensitive to r_e, and effects of Chappuis-band ozone absorption are eliminated.

Retrievals of cloud optical depth are then done by a Nonlinear Least Squares Method (NLSM), implemented though the linearized iteration described by *Bevington* [1969]. Cloud properties are treated as stationary for an arbitrary fixed interval (5 min. or 30 min.) and the retrieval done to minimize the sum of the squares of errors in transmittance for subintervals (1 min.) where the solar zenith angle is varying. The adjoint formulation of the radiative transfer greatly speeds this computation because the transmittance for all the solar zenith angles can be computed with a single adjoint radiative transfer calculation. We show results for two implementations: one where r_e is assumed to be 10 μm (comparable in methodology to the satellite retrievals), and the more complex case where r_e is permitted to vary, with the constraint from the total LWP from the microwave radiometer.

Intercomparison with the results of the GOES measurements

The ARM Spring 1994 Intensive Observing Period (IOP) operated for 21 days during April at the Southern Great Plains (SGP) Central Facility (SCF). *Minnis et al.* [1995] analysed Geostationary Operational Environmental Satellite (GOES) data for the period from April 5 to May 1, 1994 to derive cloud amount, optical depth, height, thickness, temperature, and albedo. We have chosen three overcast days, April 5, 22, and 30, 1994, to compare our inferred cloud optical depths with the results derived from the GOES measurements. On these days the cloud amounts reported by GOES measurements were 100% for all adjacent boxes and the direct irradiances of the MFRSR at the SCF were fully blocked. The surface albedo was assumed to be 0.036, as was inferred from the MFRSR clear-sky data collected at SGP site during August 1994, and total optical depth at 415 nm (Rayleigh and aerosol) of 0.425 was obtained by Langley regression on April 19, 1994.

Figures (2) and (3) show the measured and fitted transmittances, the measured and averaged liquid water paths, and the inferred cloud effective radii and cloud optical depths at the SGP site on April 22 and 30, 1994. Data taken on April 5 is used for agregate statistics shown later, but not presented in a figure to save space. The data are similar to the two cases shown, but drizzle occured, inferred effective radii are larger, and GOES retrievals identify the presence of some high-altitude clouds (that may be ice, potentially confusing the comparison). The GOES derived optical depths and their standard deviations are shown as the thick solid line in the bottom panels of each figure. Comparison of the 5-minute fitting compared to the 30-minute fitting for

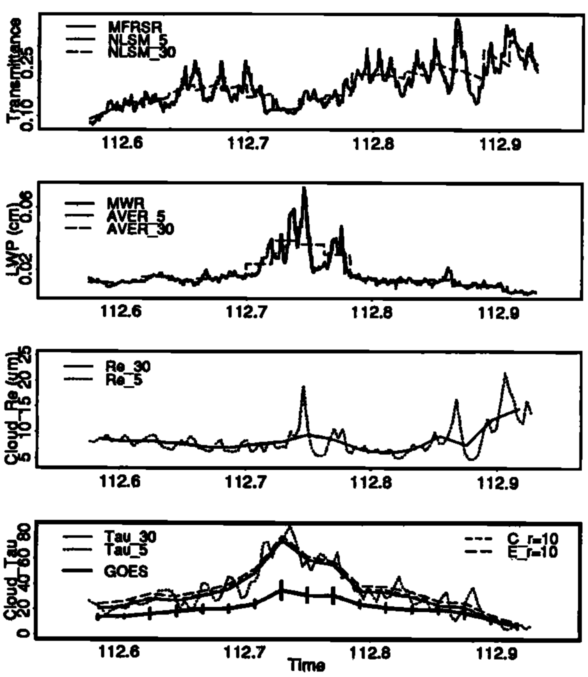

Figure 2. The measured and fitted transmittances, the measured and averaged liquid water paths, and the inferred cloud effective radii and cloud optical depths on April 22, 1994 at the SGP site (XX_5 for five minutes; XX_30 for thirty minutes). In the bottom panel, the dashed line (C_r=10) represents inferred optical depths from the complex model but fixed r_e at 10 μm; the long dashed line (E_r=10) represents inferred optical depths from the delta-Eddington model with fixed r_e at 10 μm. The GOES derived optical depths and their standard deviations are also included.

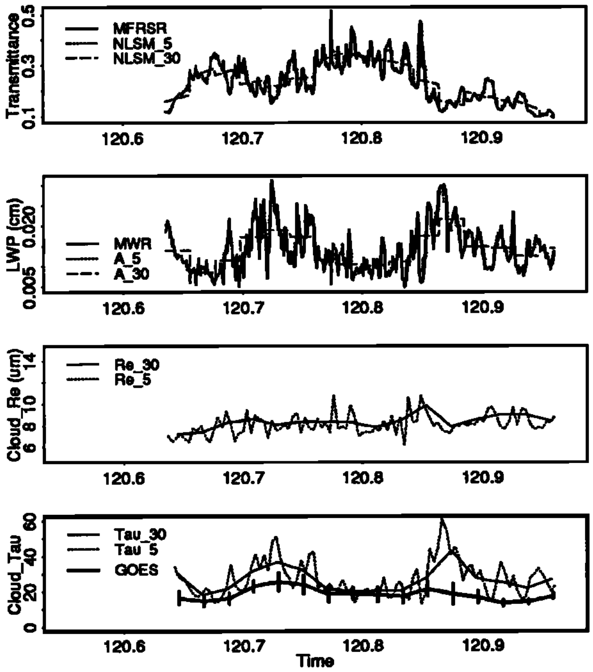

Figure 3. Same as Figure (2), but on April 30, 1994.

all three cases demonstrates that relatively constant optical depths persist for roughly 15 to 35 minutes.

On April 22, shown in Figure (2), the inferred effective radii are more typical of continental clouds, and range from 6.1 μm to 14.7 μm with average of 8.5 μm. The optical depths inferred from both the simple delta-Eddington model and the complex model with fixed $r_e = 10$ μm are also shown in the bottom panel. The simple delta-Eddington model overestimates cloud optical depths for these observations by an average of 14%. The optical depths inferred from the complex model with fixed $r_e = 10$ μm are within 3% of the results inferred when the LWP is used to also retrieve r_e. Our three surface retrieval methods produce optical depths substantially larger than the GOES retrievals, except late in the day when optical depths decline.

The results of April 30, shown in the Figure (3), again show smaller cloud effective radii from 7.2 μm to 9.8 μm with average of 8.3 μm, and the cloud optical depths range from 18 to 43 with average of 22. Temporal variations of our inferred cloud optical depths are consistent with the GOES results. However, the GOES results are substantially lower than our results except for the early morning.

Uncertainty Analysis

The large discrepancies between the optical depths inferred from the surface measurements and the GOES results demand tests of the surface retrievals for accuracy and sensitivity. As demonstrated above from the simple delta-Eddington formulation we believe that the surface-based retrievals are intrinsically more sensitive for higher-optical-depth cases. In this section we discuss potential errors that may arise from the various contributions. We show uncertainties as the fractional error in the retrieved optical depth, assessed both from the delta-Eddington formulation (evaluated as the partial derivative for $\tau = 25$), and the complex model (RMS error over the test case of April 30, 1994). These are stated as (xx,yy) where xx is the delta-Eddington uncertainty, and yy is that evaluated numerically from the more complex model.

The primary uncertainty introduced by the MFRSR measurements is that of the extraterrestrial response inferred from Langley regression. *Harrison and Michalsky* [1994] have discussed in detail the accuracy of this procedure; the standard deviation of this inferred response from single retrievals at a difficult site is approximately 5%. For our purposes this would result in an uncertainty of estimated cloud optical depths of approximately (6.7%, 6.8%).

For the 415 nm passband the inferred surface albedo was 0.036, and measured albedos taken from sensors on two separate towers at heights of 10 and 25 m were 0.030 and 0.038, respectively. A range in surface albedo of 0.031 to 0.038 produces a difference of approximately (0.5%, 0.5%). The radical assumption of zero surface albedo will decrease the inferred optical depth by roughly (3.6%, 3.7%).

Possible aerosol effects present together with the clouds are expected to be small. The impact of this can only be assessed in our more complex model. We varied the assumed aerosol optical depth 50%; the resulting changes of our inferred cloud optical properties are less than 0.5%.

The uncertainty associated with liquid water path retrievals has little impact on our retrieved τ. The optical depth is largely determined by the transmittance, and the effective radius plays only the minor role of adjusting the asymmetry factor and single scattering albedo through narrow ranges. Using the MFRSR data alone by assuming r_e of 10 μm as used in GOES retrievals, our inferred optical depths of cloud are increased for most of the data presented.

All the above retrievals were based on discrete ordinate radiative transfer calculations with 8 streams. The assumption of 8 streams in calculating the transmittance may result in 1% uncertainty of inferring the cloud optical depth. Placing the cloud layer at different heights from 1-2 km to 5-6 km has a negligible changes in the inferred cloud optical properties. The uncertainty of parameterization schemes of Mie theory (1%) may provide another 5.6%.

Satellite observations are used to assign cloud altitudes, based on the reflection and cloud temperature. A fraction of the high clouds are treated as cirrostratus clouds [*Minnis et al.*, 1995], which may result in lower cloud optical depths than that of water clouds. However, the cloud

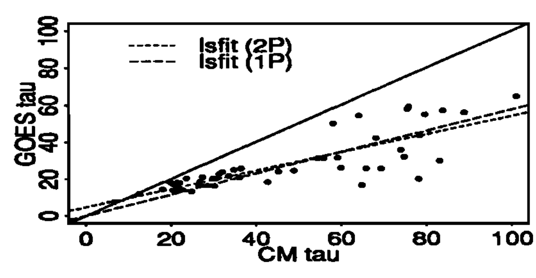

Figure 4. Correlation scattergram with a least-squares regression fit for GOES optical depths versus our inferred optical depths for the 30-minutes interval.

heights and the cloud amounts derived from GOES show that most clouds were the low-middle clouds, except for the period between 95.63 and 95.80 on April 5 where high-cloud amounts less than 40% were inferred. Therefore, our assumption of clouds dominated droplets is justified for these cases.

Figure (4) shows the correlation scattergram comparing our complex retrieval to the GOES results for all the 30 minute averaged data. The solid diagonal line is the 1:1 correlant. Computing the linear least-squares regressions for two cases, the conventional two-parameter fit, and also a one-parameter fit for the slope with the intercept forced to 0,0 yields:

	Slope	Err	y(x=0)	Err	Corr.
2P	0.492	0.048	4.83	2.47	0.88
1P	0.574	0.023	0	–	–

These statistics demonstrate that for optical depths > 10 the GOES results are approximately one-half of our surface-based retrievals, and that the conclusion that the slope of these regressions is < 1 is robust. Note that only one point, for which our retrieval yields an optical depth of 6.8, lies above the 1:1 correlant.

Subpixel inhomogeneity may result in the underestimation the cloud optical depths from satellite measurements [*Cahalan et al.*, 1994]. The satellite takes an instantaneous picture; the retrieved cloud optical depth is then averaged over 0.3° by 0.3° area (18 pixels). This is approximately 50 km, much larger than the domain sampled by the MFRSR. However the time-series show that the intervals of high optical depth are not longer in duration in the GOES data, and no averaging process could produce the consistent bias seen in figure 5. Spatial averaging cannot explain the discrepancies observed here.

Summary

We have developed an inversion method to infer the optical properties of cloud from the surface measurements by a nonlinear retrieval based on an adjoint method of radiative transfer. If the liquid water path is available (e.g. from a MWR) both the cloud optical thickness and effective radius can be simultaneously retrieved. If not the the algorithm can use a fixed effective radius; doing so increases the uncertainty by approximately 2-3%.

We have compared our results of our inversion using measurements taken at the ARM SGP site during the spring Intensive Operation Period of 1994 to GOES retrievals produced for this period. Temporal variations of the cloud optical depths are consistent between the surface and satellite measurements, and cloud optical depths agree well when the values are < 10. However, at higher optical depths the GOES results are lower by approximately a factor of two compared with ours.

This discrepancy is far too large to be explained by the estimated errors and uncertainties of the surface retrievals. The observed time-series of the data do not support spatial averaging by the satellite retrievals as the explanation. We show that top-of-the-atmosphere measurements intrinsically have poor ability to distinguish among varying large optical depths, and suggest that this bias may be general to the GOES retrievals. If so, then the ISCCP data (to which most existing climate models are tuned) substantially underestimate the optical depths for thicker low-altitude clouds.

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