A Consistency Analysis of ARESE Measurements Regarding Cloud Absorption

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Introduction

In an attempt to resolve the recent debate over the cloud absorption anomaly, the U.S. Department of Energy sponsored a field experiment in the fall of 1995 under the auspices of its Atmospheric Radiation Measurement (ARM) Program. This ARM Enhanced Shortwave Experiment (ARESE) took place around the Southern Great Plains (SGP) Central Facility (CF) in Oklahoma. Following ARESE, a cloud absorption anomaly of unprecedented magnitude and unknown origin was presented. Valero et al. (1997) employed coeval measurements of upwelling and downwelling radiative fluxes made on two stacked aircraft (above and below clouds) and reported that cloud absorption increases dramatically with cloud fraction. For a heavy overcast (October 30, 1995), they claimed that the layer between the aircraft (mostly cloud) absorbed 37% of the incoming solar irradiance. This contrasts sharply with model estimates of total atmospheric absorptance, which are usually around, or less than, 24% regardless of sky condition (Li et al. 1997). If clouds on October 30 were indeed so absorptive and representative, other relevant radiometric measurements should be able to detect such a strong signal. The purpose of this study is to examine if measurements made by other instruments support the finding of Valero et al. (1997).

Data

The study employed measurements of solar radiation made by space-borne, air-borne, and ground-based radiometers over the SGP CF site in Oklahoma (36.605°N, 97.485°W).

Satellite data include measurements from the Scanner for Earth Radiation Budget (ScaRaB) onboard Meteor 3 satellite and the Visible and Infrared Spin-Scan Radiometer (VISSR) onboard Geostationary Operational Environmental Satellite (GOES)-7 and GOES-8. ScaRaB provided calibrated shortwave (SW) (0.2 µm to 4.8 µm) and visible (~0.6 µm) reflected flux/albedo measurements at a spatial resolution of about 60 x 60 km at nadir with varying equator-crossing time. It operated from February 1994 through March 1995. The calibration accuracy is estimated to be 1% to 2% (Kandel et al. 1998; Trishchenko and Li 1998). While GOES provides data at much higher temporal (every 15 to 30 minutes) and spatial (about 1 km at nadir viewing) resolutions than ScaRaB data, it has no on-board calibration. Minnis et al. (1995) applied an indirect post-launch calibration to obtain visible albedos that were then used to derive SW albedos by means of narrowband-to-broadband conversion. Both the calibration and narrowband-to-broadband conversion used in processing GOES-7 data were validated against ScaRaB measurements

(Trishchenko and Li 1998). Calibration for GOES-8 was based on a Comparison with National Oceanic and Atmospheric Administration (NOAA)-14 advanced very high resolution radiometer (AVHRR) measurements.

Aircraft observations were made during the ARM ARESE experiment which took place between September 22 and November 1, 1995. Three aircraft were involved: the ER-2 flew at 20 km, the Egrett flew at 14 km, and the Twin Otter flew between 0.5 km and 2 km. Each aircraft was equipped with two zenith- and nadir-pointing Total Solar Broadband Radiometers (TSBRs) that measured total solar irradiance between 0.224 µm and 3.91 µm, and the Total, Direct, Diffuse Radiometers (TDDRs) that measured 10-nm wide spectral bands centered at seven wavelengths between 0.5 µm and 1.75 µm (Valero et al. 1997). Four days worth of data, with varying degrees of cloudiness, were analyzed by Valero et al. including a cloudless day (October 11), a day with scattered clouds (October 19), a day with broken clouds (October 13), and a heavy overcast day (October 30). For ease in matching air-borne and space-borne measurements, aircraft data used in this study were restricted to the overcast day.

In addition, the Egrett was equipped with a downfacing, spectrally scanning polarimeter (SSP) (Stephens et al. 1998). The calibration for the instrument employs an integrating sphere with standard lamps and accounts for the spectral, angular and temperature responses. It measures reflected solar flux from approximately 0.4 µm to 1.1 µm with a spectral resolution varying from approximately 0.015 µm to 0.03 µm. To obtain SW albedos at the top of the atmosphere (TOA) from these spectral fluxes for comparison with satellite observations, narrowband visible albedos are first computed at the Egrett altitude and then converted to TOA values. The conversions were made by modeling with a two-stream radiative transfer model. The narrowband spectral albedos were then integrated over the ScaRaB visible bandpass and weighted by its spectral response function. The resulting ScaRaB equivalent visible albedos at the aircraft's altitude are further corrected to TOA visible albedo by means of radiative transfer modeling. From these equivalent ScaRaB visible albedos at the TOA, SW albedos were derived using an observational narrowband-to-broadband conversion relation derived from ScaRaB over the SGP region. The conversion is accurate to within 2%.

Surface irradiance measurements made at the SGP site were employed from 1994 to 1996. They were made with an observing system known as the Baseline Surface Radiation Network (BSRN). The system consists of shaded and unshaded broadband pyranometers and pyrheliometers. The quality of the data was assessed by comparing measurements to the much more reliable cavity radiometer and an independent standard system called the Solar and Infrared Radiation Observation System (SIROS) (Michalsky et al. 1997). After corrections, measurements of total irradiance at the surface from these instruments agree to be within 10 Wm^{-2}.

Comparison

To compare albedos observed by an airborne radiometer with a hemispheric field of view (FOV) with those by a space-borne radiometer with a much narrower FOV, GOES reflectance measurements were integrated over the hemispheric domain:

$$\alpha(\theta_0) = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} \rho'(\theta_0, \theta', \phi') \sin\theta \cos\theta \, d\theta \, d\phi \qquad (1)$$

where $\rho'(\theta_0, \theta', \phi')$ is bidirectional reflectance in the direction given by a viewing zenith (θ') and a relative azimuth (ϕ') with respect to the aircraft. Since the viewing geometry with respect to the aircraft $(\theta_0, \theta', \phi')$ differs from that to the satellite (θ_0, θ, ϕ), $\rho'(\theta_0, \theta', \phi')$ is obtained from $\rho(\theta_0, \theta, \phi)$:

$$\rho'(\theta_0, \theta', \phi') = \frac{\Omega(\theta_0', \theta', \phi')}{\Omega(\theta_0, \theta, \phi)} \rho(\theta_0, \theta, \phi) \qquad (2)$$

where Ω denotes the bidirectional reflectance distribution function (BRDF) given by Minnis and Harrison (1984). After visible albedos were obtained, they were converted into SW albedos using a narrowband-to-broadband conversion model (Li and Trishchenko 1997).

Figure 1 shows TOA albedos obtained from the TSBR, GOES-8, and SSP on October 30, 1995. The curve denoting albedos derived from GOES-8 are discontinuous as the GOES images were separated by approximately 15 minutes. Cloud reflectances were assumed to remain invariant during this interval. It is seen that fluctuations in albedo, as measured by the aircraft, are similar to those inferred from satellite radiances, but the magnitudes of albedos inferred from GOES, TSBR, and SSP differ drastically. The mean-bias difference is 6% between GOES and TSBR and about 14.4% between SSP and TSBR. The disparity in albedo is comparable to the magnitude of the cloud absorption anomaly (CAA) reported by Valero et al. (1997).

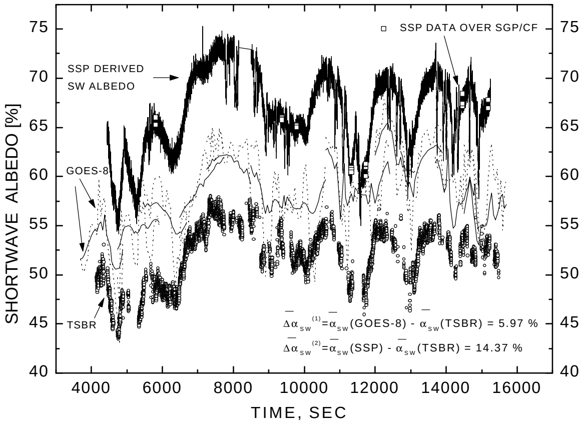

Figure 1. Comparisons of TOA albedos inferred from measurements made by the TSBR, GOES-8, and SSP. Two sets of GOES-based estimates are shown for an aircraft along the Egrett's flight path: one for an aircraft skimming the cloud tops (dotted lines); and another for one at 14 km (thin solid lines). Squares represent SSP measurements made near SGP/CF.

To understand the discrepancies, comparisons were made between ScaRaB, GOES-7, GOES-8, and SSP. For the ARM experiment, GOES-8 data were made available in 1995 and 1996 (Minnis and Smith 1998), GOES-7 and ScaRaB in 1994. The difference in time and strong cloud variability make the direct comparison of TOA albedos meaningless. However, it is revealing to compare the relationship between TOA albedo and surface transmittance. The slope of the relation was proposed to assess cloud absorption by Cess et al. (1995). Although the slope can be an ambiguous indicator of cloud absorptance (Li and Moreau 1996; Barker and Li 1997), it is much less variable than TOA albedo and atmospheric transmittance, especially for overcast scenes. For broken clouds, the approach suffers from considerable uncertainties due to large errors in matching TOA and surface measurements (Arking et al. 1996) and to horizontal transport of photons (Barker and Li 1997). Given these limitations, all matched pairs of TOA and surface measurements were screened based on the standard deviation (SD) of surface irradiance. Because partly cloudy scenes evolve more rapidly than do clear and overcast scenes, data were retained if the SD was less than 20 Wm^{-2}.

Figure 2 presents an albedo-transmittance plot for screened data. TOA albedos were derived from GOES-7, GOES-8, ScaRaB, and SSP. GOES data represent averages over grid-cells of 0.3° x 0.3° centered at the ARM CF, and ScaRaB data are for individual pixels closest to the CF. SSP data

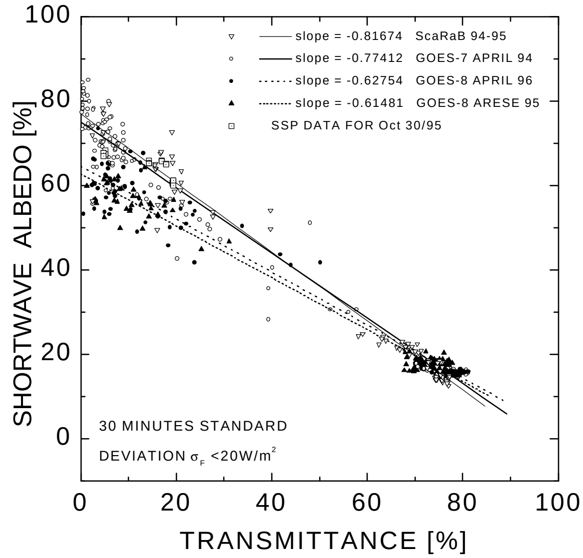

Figure 2. The relations between TOA albedo and atmospheric transmittance. TOA albedos were derived from GOES-8 for ARESE for April 1996, from GOES-7 for April 1994, from ScaRaB for 1994, and from SSP for October 1995. Atmospheric transmittance was computed from surface irradiance measurements from BSRN. Regression equations are listed on the plot.

were taken within 1 km around the CF for homogeneous cloud scenes. Atmospheric transmittances were computed from broadband surface irradiances observed with BSRN at the CF. Due to the data screening, the majority of data points correspond to either clear or overcast scenes. The most striking feature of Figure 2 is the tight cluster of clear-sky points on the right, and the presence of two distinct clusters on the left (overcast). One cluster consists of data from GOES-7, ScaRaB, and SSP while the other consists of GOES-8 data. The slopes for the least-square linear regression lines for GOES-7 (-0.78) and ScaRaB (-0.82) data are indistinguishable from model values (~0.8) (Cess et al. 1995; Li and Moreau 1996). The SSP data points distribute closely around the regression lines of ScaRaB and GOES-7. This finding contradicts the existence of a significant cloud absorption anomaly. Indeed, atmospheric absorptances computed from ScaRaB, TOA and surface measurements show no systematic difference between clear and overcast skies (see Figure 3) for the data collected in 1994. The regression slope for GOES-8 data, however, is significantly smaller than the others.

If all measurements are correct, one has to conclude that clouds in 1995 and 1996 were anomalously absorptive relative to those in 1994. This conclusion is difficult to

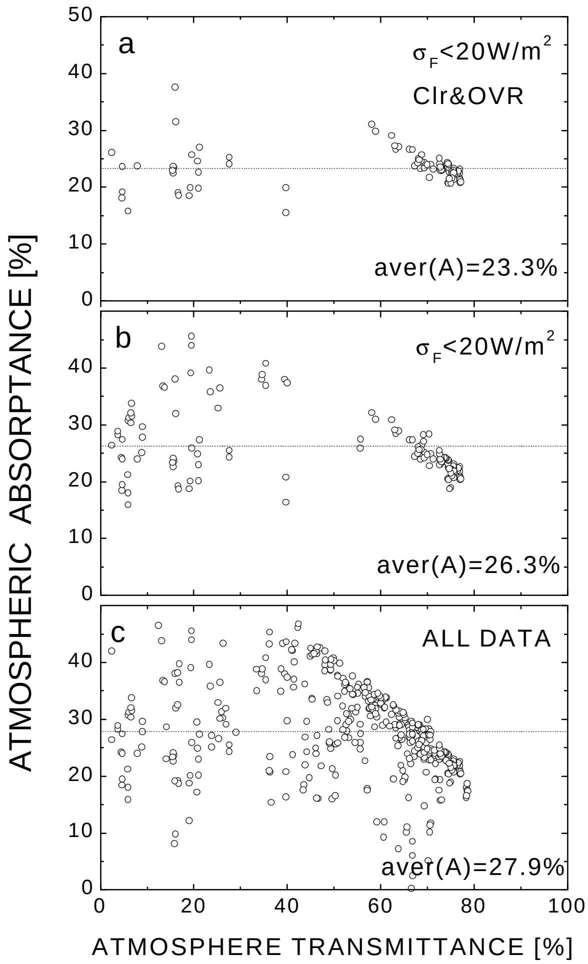

Figure 3. Atmospheric absorptance computed from satellite (ScaRaB) and surface (BSRN) measurements from March 1994 to February 1995 at the SGP/CF. Data for inhomogeneous clouds were screened out by restricting the standard deviation of 30-minute surface observations to less than 20 Wm^{-2}.

accept, barring protracted, yet intermittent, environmental changes that produced dirty clouds over the period and location in question. To our knowledge, this did not occur. A more sound explanation lies within the inconsistent calibration in processing GOES-7 and GOES-8 data. Calibration for GOES-7 has been validated against ScaRaB (Trishchenko and Li 1998), which is further reinforced by the results in Figure 2. GOES-8 was calibrated relative to AVHRR/NOAA-14. Since AVHRR did not have on-board light sources for calibration, the coefficients of the NOAA-14 calibration were determined by observations made over a stable desert surface (Rao and Chen 1996). The calibration inconsistency is more evident from a comparison of visible albedos observed by GOES-8 and computed from SSP measurements weighted by the GOES-8 response function in the visible band (see Figure 4).

Similar inconsistent results were obtained by Dong et al. (1998). They first retrieved cloud properties using ground-based measurements of cloud liquid water path from a microwave radiometer, cloud base from the laser ceilometer, cloud top from radar, solar flux from Eppley precision spectral pyranometer (PSP), and soundings from radiosondes. TOA albedos were then computed with a two-stream radiative transfer model and compared with those derived from GOES-7 and GOES-8. Excellent agreement was achieved for GOES-7 during April 1994, but GOES-8 TOA albedos were generally less than those deduced from ground-based measurements by about 15%.

Other potential contributing factors to the discrepancy may be differences in the calibrations of the BSRN radiometers used in April 1994 and October 1995 and uncertainty in the SSP calibrations. The calibration uncertainty in SSP flux measurements is determined to be 3% to 5% (relative) for most of the spectrum, relative to an isotropic calibration source (Stephens et al. 1998). Because the cosine response is not perfect (deteriorates beyond 65° to 70°), it may change, in principle, with the scene viewed. This was found not to be a significant problem when compared to other instruments (e.g., TDDR) with different cosine responses for a variety of scenes. The precision of calibration is generally higher (in the order of 1% to 2%) across the visible and a little less across the near infrared.

Since the albedos observed by TSBR are the lowest (6% less than those from GOES-8), an even larger calibration uncertainty for TSBR certainly cannot be ruled

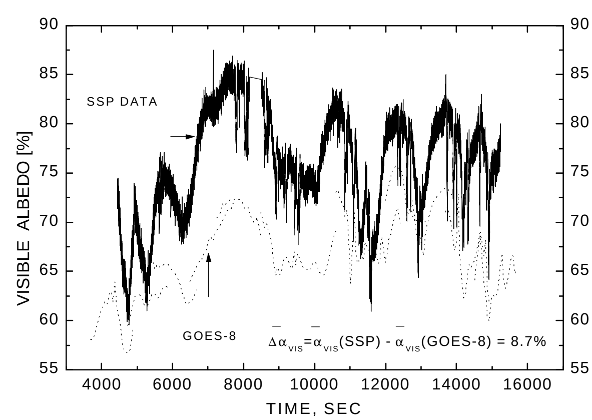

Figure 4. A comparison of TOA visible albedos inferred from both GOES-8 (dash line) and SSP (solid line) data in which the SSP used GOES-8's response function.

out. Thus, it is imperative to solve the calibration conundrum before accepting the conclusion of the existence of an enormous CAA, as found by Valero et al. (1997).

Summary

Following the ARM/ARESE experiment, Valero et al. (1997) showed a CAA of unprecedented magnitude. An analysis is presented here to examine if their finding is consistent with observations from multiple sensors on various platforms including those onboard satellites (ScaRaB, GOES), aircraft (TSBR, SSP), and on the ground (BSRN). It was found that albedos measured with the TSBR radiometer, as used by Valero et al. (1997), were systematically less by 0.06 and 0.144, respectively, than values estimated from GOES-8 imagery and SSP. The discrepancy appears to stem from inconsistent calibrations among the radiometers. An analysis of the regression between TOA albedo and atmospheric transmittance revealed nearly identical slopes derived from SSP, ScaRaB, and GOES-7, which are in excellent agreement with model values and at variance with the finding of Valero et al. (1997).

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