Comparison of ScaRaB, GOES 8, aircraft, and surface observations of the absorption of solar radiation by clouds

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[1] Data obtained by the Scanner for Radiation Budget (ScaRaB) instrument on the Meteor 3 satellite have been analyzed and compared to satellite (GOES 8), aircraft (Radiation Measurement System, RAMS), and surface (Baseline Solar Radiation Network (BRSN), Solar and Infrared Observations System (SIROS), and RAMS) measurements of irradiance obtained during the Atmospheric Radiation Measurements Enhanced Shortwave Experiment (ARESE). It is found that the ScaRaB data covering the period from March 1994 to February 1995 (the instrument's operational lifetime) indicate excess absorption of solar radiation by the cloudy atmosphere in agreement with previous aircraft, surface, and GOES 8 results. The full ScaRaB data set combined with BSRN and SIROS surface observations gives an average all-sky absorptance of 0.28. The GOES 8 data set combined with RAMS surface observations gives an average all-sky absorptance of 0.26. The aircraft data set (RAMS) gives a mean all-sky absorptance of 0.24 (for the column between 0.5 and 13 km). *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0394 Atmospheric Composition and Structure: Instruments and techniques; 1610 Global Change: Atmosphere (0315, 0325); *KEYWORDS:* radiation, absorption, clouds, observations

1. Introduction

[2] One of the fundamental questions in climate science today is how much solar radiation the atmosphere absorbs. Recently, numerous attempts have been made to answer this question for clear and cloudy atmospheres. Historically, theoretical predictions do not agree with many aircraft, surface, and satellite observations for cloudy conditions, whereas predictions for the clear atmosphere appear to be accurate within model and experimental errors. However, such agreements or disagreements are the subject of many debates within the climate-radiation scientific community. In this study, data from the Scanner for Radiation Budget (ScaRaB) instrument [*Kandel et al.*, 1998] on the Meteor 3 satellite are combined with surface measurements in an effort to contribute more information that may help solve the excess (relative to models) cloud absorption issue.

[3] Different data sets collected during the Atmospheric Radiation Measurements Enhanced Shortwave Experiment (ARESE) have been previously analyzed to estimate the absorption of solar radiation in the clear and cloudy atmosphere [*Zender et al.*, 1997; *Valero et al.*, 1997; *Li et al.*, 1999; *Cess et al.*, 1999; *Pope and Valero*, 2000]. This experiment took place in 1995 and involved radiometers on the surface, on three aircraft at 0.5-, 13-, and 20-km altitude and on a satellite. The data from the aircraft radiometers were combined to determine the amount of absorption in the column of atmosphere between 0.5 and 13 km, while the surface and satellite data were combined to address the absorption in the entire column. In both cases the amount of absorption was found to increase with increasing cloud amount and to be in excess of model predictions [*Valero et al.*, 2000].

[4] Although not collected during the same time period, the ScaRaB data set from March 1994 to February 1995 can be combined with simultaneous, collocated surface measurements to provide an additional means of assessing atmospheric absorption. This combined data set contains measurements of clear, partly cloudy, and overcast sky conditions and is centered at the same geographical location as ARESE. The results obtained from the analysis of the ScaRaB data set are compared to ARESE results.

2. Data

[5] The data set referred to here as the ScaRaB data set combines measurements of top-of-atmosphere (TOA) albedo from the ScaRaB instrument on the Meteor 3 satellite with surface flux measurements. These surface measurements are from the Baseline Solar Radiation Network (BSRN) and Solar and Infrared Observations System (SIROS) located at the Atmospheric Radiation Measurements (ARM) program Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site near Lamont, Oklahoma. (This was also the surface site for ARESE.) All measurements are for the time period March 1994 to February 1995. Each satellite observation is matched with a 30-min average surface data

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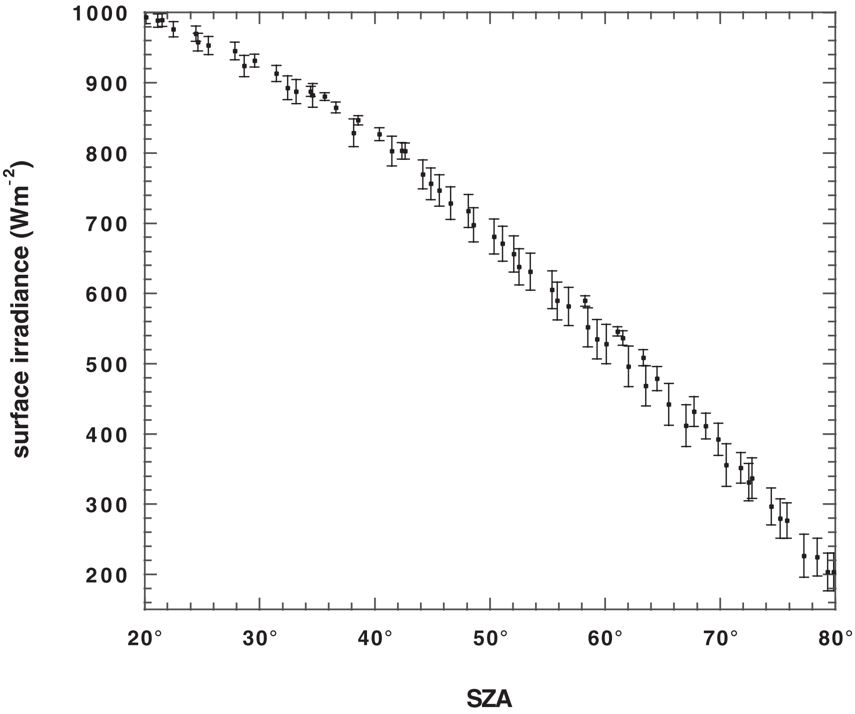

Figure 1. Representative solar zenith angles (SZAs) and times of day were selected from the ScaRaB data set. A "synthetic" surface flux for clear sky conditions, simply equal to 75% of the TOA downwelling flux, is shown as a function of SZA. The error bars indicate the standard deviation in a 30-min average, assuming stable sky conditions. For SZAs greater than ~40° the standard deviation (due to the changing sun angle in the 30-min period) can exceed 20 Wm^{-2}.

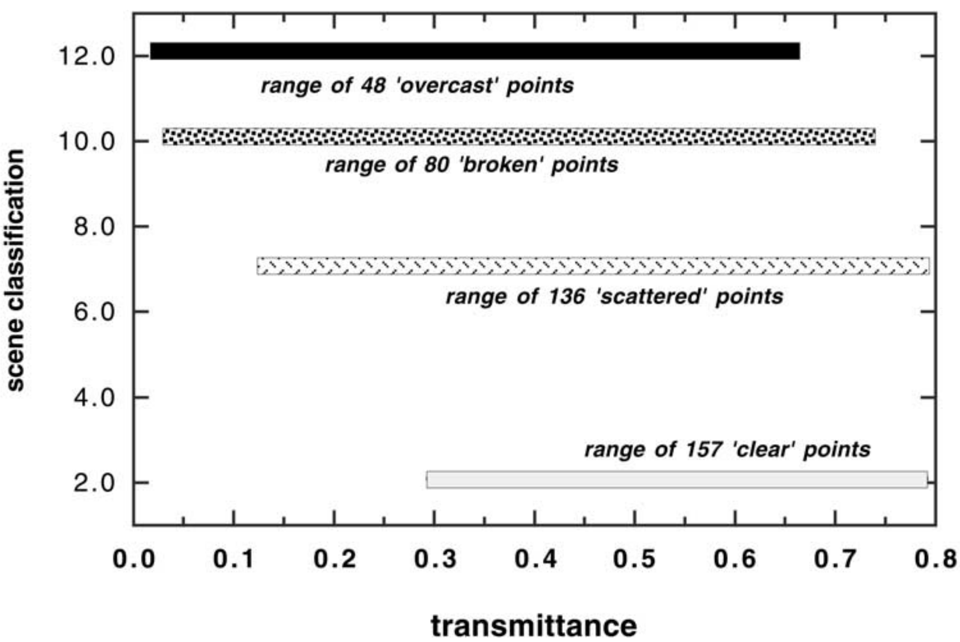

Figure 2. Scene classification algorithm applied to the ScaRaB data results in each point being assigned to a cloud condition. The range of (surface) transmittance values for each of the scene classifications is shown. The pronounced overlap in surface transmittance between the four different scene classifications shows the inconsistency between surface-based scene and satellite-based scene.

Table 1. Mean All-Sky Absorptance

Selection	Case	Number of Points	Mean Absorptance
All (Figures 3 and 4)	A	421	0.28 ± 0.03
Satellite scene classification matches surface scene classification	B	216	0.26 ± 0.03
All, with $44° \leq$ SZA $\leq 66°$	C	113	0.28 ± 0.03
Subset of case B with $44° \leq$ SZA $\leq 66°$	D	51	0.28 ± 0.04
ARESE GOES 8/RAMS		139	0.26 ± 0.03

point, and the entire combined data set contains 421 such matched data points.

3. *Li et al.* [1999] Slope Analysis

[6] One method of analyzing such a data set is to plot albedo, or reflectance R, versus transmittance T of the surface-to-TOA column. The slope of the RT plot is termed β, and its magnitude is compared to model values as an indicator of enhanced absorption. *Li et al.* [1999] present such an analysis of this ScaRaB/BSRN data set and find an RT slope of -0.82. They conclude that since this value is indistinguishable from typical model values of approximately -0.8, the data show no evidence of enhanced absorption. The data set used to draw this conclusion is a subset, consisting of only ~21% of the entire available data set, which results from the application of two selection criteria. The first selection criterion applied to the data is to eliminate all points for which sigma, the standard deviation in the 30-min average of the downwelling fluxes at the surface, is greater than 20 Wm^{-2}. The goal of this criterion was to exclude highly variable partly cloudy scenes. However, for SZAs greater than ~40° sigma can exceed 20 Wm^{-2} even in perfectly clear stable conditions due to the changing SZA over the 30-min period of the average, as illustrated in Figure 1. Thus data points in clear-sky conditions with SZAs greater than 40° will be erroneously eliminated by this selection criterion.

[7] The second selection criterion excluded points that do not have satellite scene classifications of either clear or overcast, again with the goal of eliminating any rapidly changing scenes. These satellite scene classifications come from the ScaRaB data processing team, which classified each data point as corresponding to clear, scattered, broken, or overcast sky conditions using the scene identification algorithm employed for Earth Radiation Budget Experiment (ERBE) [*Wielicki and Green*, 1989]. However, satellite

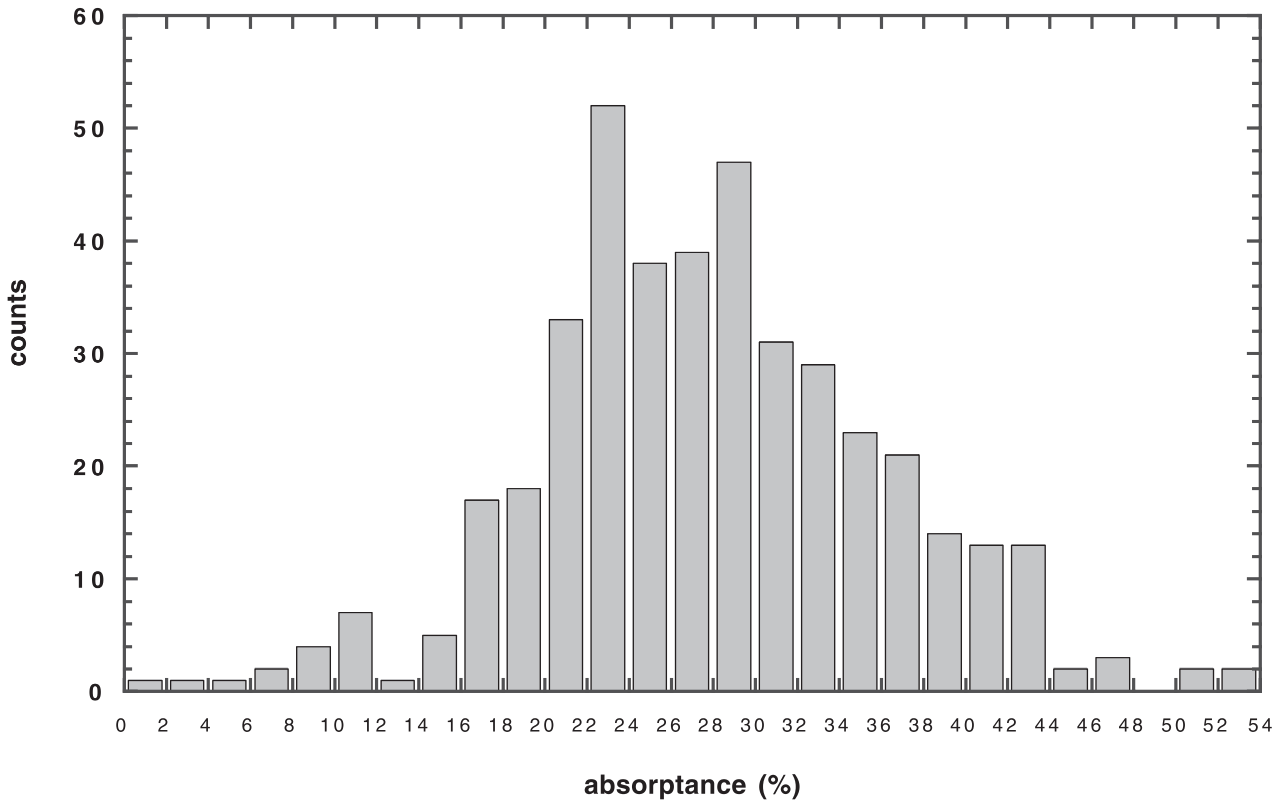

Figure 3. Frequency of occurrence of absorptance values in the ScaRaB/BSRN data set is shown in a histogram.

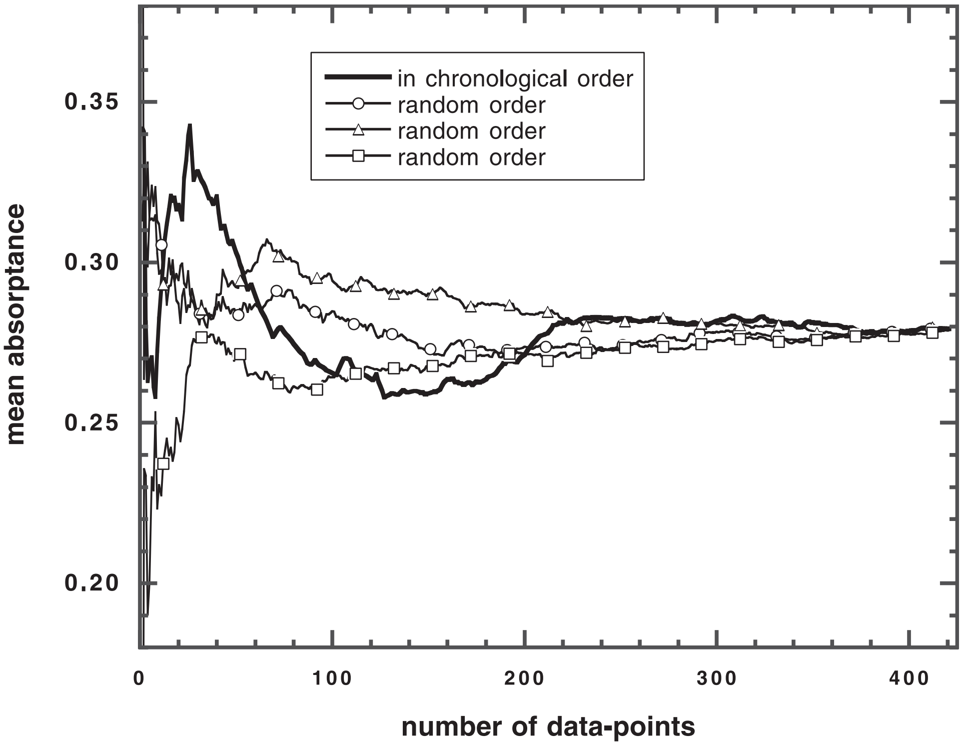

Figure 4. For the entire data set the cumulative average of the absorptance is calculated as a function of number of data points. Regardless of the order of the points, a stable mean is achieved with ~250 points.

scene and surface scene (as gauged by the surface transmittance) do not always correlate well in this data set. Figure 2 shows that there is considerable overlap between the different satellite scenes' ranges of transmittance; even the clear and overcast points have significant overlap. These apparent inconsistencies may result from the difference between ScaRaB resolution (~3000 km^2 pixels) and the footprint of the surface radiometers (~50 km^2). Also, surface observations are not strictly collocated with the ScaRaB measurements; ScaRaB pixels are included in the data set if the center of the pixel is within 30 km of the CART site. A localized clear-sky or inhomogeneous cloud cover seen by the surface instruments may be included in an otherwise overcast pixel as seen by the satellite. Similarly, the surface instruments may be directly under a localized cloud in a scene that is mostly clear as seen by the satellite. Thus satellite scene classification in this particular case should not be used as a selection criterion for a data set involving combined satellite and surface data. Such a criterion results in erroneous elimination of data points.

[8] Apart from the selection criteria used on the data set, there are numerous drawbacks to the RT slope method itself. *Barker and Li* [1997] analyzed a similar satellite and surface data set and found that there are problems with matching measurements from a single point on the surface to measurements from a satellite. The satellite overpass is essentially instantaneous and covers a large spatial area; the surface instrument sees a smaller spatial area but is averaged over an hour with the intent to encompass the clouds seen by the satellite. The result is that the atmospheric column for the measurements is ill defined and so R and T are poorly correlated. In their conclusions, Barker and Li state that the main point of their paper is that linear regression parameters (i.e., the slope β) obtained by fitting R and T cannot be compared with one-dimensional (1-D) model values of the slope as a means of assessing excess cloud absorption.

[9] Another criticism of the slope method is discussed by *Arking et al.* [1996], who argue that the linear fit should be between T and R rather than R and T. However, the slopes that result from the different fits are related by the square of the correlation factor, as they note. Thus, when R and T are well correlated, the correlation factor is close to one and the slopes from either fit are nearly equivalent. When R and T are not well correlated, as may be the case where satellite overpasses are not well collocated with the surface instruments, then it stands to reason that parameters derived from a linear fit may not be robust enough to interpret with any confidence. *Imre et al.* [1996] also criticize the slope method because it must be assumed that clear-sky and cloudy-sky points both fit the same line.

4. Mean Absorptance

[10] An alternative method of analyzing this data set is to calculate the mean absorptance of the column. To do this, one needs upwelling and downwelling fluxes at TOA and at the surface. The satellite provides the TOA fluxes and the BSRN and SIROS provide the surface fluxes. Absorptance is calculated directly from these quantities and does not depend on any fit to the data.

[11] The mean all-sky absorptance for the entire data set of 421 points (Table 1, case A) is 0.28 ± 0.03. Figure 3 shows a frequency distribution of the absorptance values in a histogram. This compares well to an all-sky absorptance of 0.26, which was obtained for the ARESE time period using Radiation Measurement System (RAMS) data [*Valero et al.*, 2000] combined with

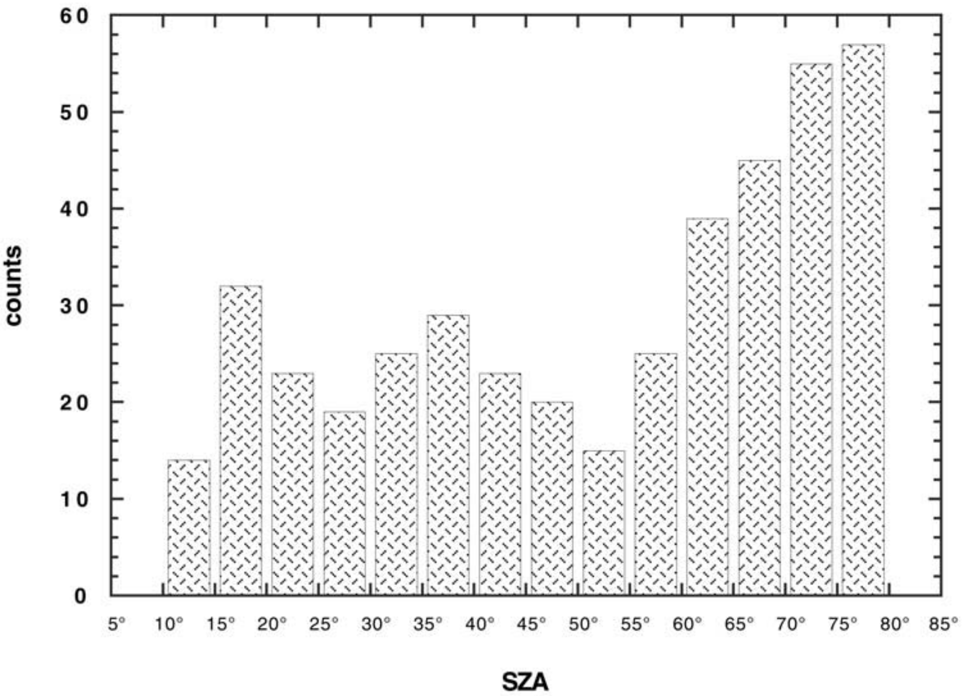

Figure 5. Histogram showing the frequency of occurrence of solar zenith angles for the ScaRaB/BSRN data set. The data set is heavily biased toward high SZAs: over one third of the points have SZA > 65°.

the eighth Geostationary Operational Environmental Satellite (GOES 8) data [*Minnis et al.*, 2002]. It should be noted that a comparison of clear-sky surface radiation measurements during ARESE [*Bush and Valero*, 1999] indicated that the BSRN irradiances are a few percent lower than RAMS irradiances for clear skies and somewhat higher for cloudy skies (likely due to thermal offsets [*Bush et al.*, 2000]). If one were to adjust the BSRN data in this data set to correct for this difference the mean absorptance would be slightly affected. However, the comparison between the two sets of ground instruments in cloudy conditions is not known well enough to apply such a correction to the entire clear and cloudy data set.

[12] Cumulative averages of the data, as discussed by *Marshak et al.* [1997] and *Valero et al.* [2000], help to assess whether the number of data points is sufficient to render stable averages that are representative of the data set. As shown in Figure 4, the cumulatively averaged absorptance has been calculated (directly from net fluxes) using the data points in chronological order and in three randomly ordered sets. The stable average value is achieved with a sampling error within ±0.01 at ~250 data points. Figure 4 illustrates that the number of data points is sufficient to achieve a stable average for the mean absorptance. Note that the mean value of the absorptance represents all-sky conditions: cloudy, broken, and overcast.

[13] To explore possible effects of the satellite-surface scene mismatch on the mean absorptance, a double criterion was applied to the data set. This criterion selected out only points that have the same scene classification determined from both the surface and the satellite. Applying this double criterion results in a set of 216 data points (Table 1, case B), where points with surface transmittance values of greater than 0.7 were considered clear, points with transmittance values between 0.4 and 0.7 were considered scattered, and points with transmittance values of less than 0.4 were deemed overcast. Following an analysis like that in Figure 4, the all-sky mean average absorptance can be determined with a sampling error of about ±0.01 for this data set. For this case, case B, the mean all-sky absorptance is 0.26 ± 0.03.

[14] The effect of solar zenith angle (SZA) on the mean absorptance was also explored. As illustrated in Figure 5, the ScaRaB data set is heavily biased toward points measured at high SZAs. For example, out of the total of 421 points, there are 157 points (over one third) with SZA greater than 65°. For SZA >70° the incident signal is very low, which may increase uncertainty in the measurements. It is of particular interest to compare the ScaRaB/BSRN results with the results obtained during ARESE. Because the ARESE aircraft observations were made only for SZAs between 44° and 66°, case C is the subset of case A (all data points) containing only points with $44° \leq \mathrm{SZA} \leq 66°$. There are 113 points in case C (Table 1), and the mean all-sky absorptance is 0.28.

[15] Case D (Table 1) is the subset resulting from the intersection of case B (which required surface scene classification and satellite scene classification to be consistent) and case C. For a total of 51 points in this case the mean all-sky absorptance is 0.28.

5. Discussion

[16] The resulting mean all-sky (clear, cloudy, broken, and overcast) absorptances for these cases are shown in Table 1. The ScaRaB/BSRN all-sky average absorptance measurements, at around 0.26 to 0.28, indicate enhanced absorption relative to a standard DISORT model estimated mean absorptance of 0.20. The mean absorptance value is not greatly affected by the selection made upon the ScaRaB/BSRN data set. Cases A through D give mean absorptances that are consistent with one another and with the GOES 8/RAMS mean absorptance.

[17] It should be noted that the GOES 8 calibration has been revised recently. *Minnis et al.* [2002] found that the Visible Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission satellite could provide a more reliable calibration for GOES 8 than the Advanced Very High Resolution Radiometer on NOAA 14 that was used by *Valero et al.* [2000]. The new calibration source resulted in an 8.5% increase in the GOES 8 gain, which corresponded to an increase in mean absorptance from 0.25 to 0.26.

6. Conclusions

[18] *Li et al.* [1999] used specific criteria on this data set and computed the *RT* slope. On the basis of its value of −0.82 they concluded that the data show no evidence for enhanced absorption. However, that conclusion is based on (1) selection criteria that have been shown to eliminate points erroneously and (2) the slope method that relies on a linear fit between *R* and *T*.

[19] The mean absorptance of the ScaRaB/BSRN data set is a more straightforward measure of absorption in the sense that it does not depend on any fit between *R* and *T*. The mean absorptance of the ScaRaB/BSRN data set is 0.28, which agrees well with both the ARESE aircraft value of 0.24 (for 0.5 to 13 km) and the GOES 8/RAMS value of 0.26. Selecting various subsets of the ScaRaB/BSRN data set, based on matching surface and satellite scenes and on solar zenith angle range, has little effect on the mean absorptance: the values are consistently in the 0.26 to 0.28 range. This is significantly higher than a mean all-sky absorptance computed from a standard DISORT model and so indicates that such models are underestimating the amount of solar energy being deposited into the atmosphere in the presence of clouds.

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