Comparison of ARM GOES-Derived Broadband Albedos with Broadband Data from ARM-UAV and ScaRaB

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Introduction

Broadband radiative fluxes, shortwave albedo (SWA) and outgoing longwave radiation (OLR), provide energy constraints on the earth-atmosphere system. As such, they are fundamental parameters that must be accurately computed in climate simulations. Thus, they must also be accurately measured. Unfortunately, the availability of top-of-atmosphere (TOA) broadband data measured from satellites is limited in temporal and spatial coverage. Except for the Earth Radiation Budget Experiment (ERBE) wide field of view (WFOV) data, satellite-measured broadband flux data are unavailable between February 1995, when the Scanner for Radiation Budget (ScaRaB) failed, and January 1998 when the Clouds and Earth’s Radiant Energy (CERES) experiment began. When the typical broadband satellite data are available, they are limited in temporal sampling, usually twice a day per satellite. Furthermore, the broadband nominal footprints are relatively large, 32 km for ERBE on the Earth Radiation Budget Satellite (ERBS) (Smith et al. 1986), 60 km for ScaRaB on the METEOR-3 (Kandel et al. 1993), and 10 km CERES on the Tropical Rainfall Monitoring Mission (TRMM) satellite (Wielicki et al. 1995).

The Geostationary Operational Environmental Satellite (GOES) can provide much better temporal and spatial sampling of the fluxes but is limited by its narrowband measurements. Thus, the narrowband data are used to estimate the broadband fluxes. The method for converting narrowband radiances to broadband fluxes for the Atmospheric Radiation Measurement (ARM) Program is based on historical measurements from GOES collocated with ERBE-scanner broadband data. Broadband fluxes are computed from the GOES narrowband radiances along with cloud properties on a 0.5° grid bounded by 42°N to 32°N and 105°W to 91°W (Minnis et al. 1995). The narrowband-to-broadband relationship can be applied to individual GOES pixels with a 1-km nominal resolution. The validation of these narrowband-based broadband fluxes is critical to establishing a stable, long-term flux dataset for ARM. In this paper, other broadband data are used to estimate the errors in the GOES-derived fluxes. GOES-7 SWAs are verified with ScaRaB during 1994. GOES-8 SWA is compared with the Total Solar Broadband Radiometers (TSBR) mounted on the Egrett and Otter aircraft during the ARM Enhanced Shortwave Experiment (ARESE) of October 1995. Finally, GOES-8 SWA is also compared against the ERBS-WFOV SWA during 1994-1996.

GOES Data

The visible (VIS, 0.65 μm) GOES radiances are calibrated against the visible channels of the National Oceanic and Atmospheric Administration (NOAA)-advanced very high resolution radiometer (AVHRR) because they have been reliably calibrated against a stable desert target over many years. The calibration of GOES VIS data is described in Ayers et al. (1998). To estimate SWA, the narrowband VIS radiances, L, are converted to VIS albedo,

$$\alpha_n = \pi L / \left[\delta(d)\, \mu_o\, E\chi(\mu_o, \mu, \psi)\right]$$

where δ is the earth-sun-distance correction factor for Julian day d, E, the VIS solar constant for GOES, is 526.9 $Wm^{-2}sr^{-1}\mu m^{-1}$, μ_o and μ are the cosines of the viewing and solar zenith angles, ψ is the relative azimuth angle, and χ is the bidirectional reflectance model described by Minnis and Harrison (1984). The bidirectional model depends on the scene with distinct values for three surface types: clear water, land, and clouds. If the scene is mixed, albedos are calculated for each surface type, then averaged according to the weight of each surface type.

Baseline Narrow-to-Broadband Model

Broadband SWA from ERBE 2.5° latitude and longitude gridded S9 data product were matched within the nearest local half hour of GOES-6 narrowband SWA for the month of October 1986. Only data from the ERBS satellite was used because it has a precessing orbit, which allows it to sample 12 local hours in 36 days. Data from the NOAA-9 satellite would bias the regression coefficients to afternoon conditions. The spatial domain of the data was bounded by 32.5°N, 42.5°N, 95°W and 105°W. The data were regressed following Minnis et al. (1995) to yield the following equation applicable to both cloudy and clear scenes,

$$\alpha_b = 0.0571 + 0.720\alpha_n + 0.0287\alpha_n^2 + 0.0523\ \ln(1/\mu_o)$$

where α_b is the broadband albedo. ERBS viewing zenith angles were limited to 45° and solar zenith angles (SZAs) to less than 84°. The resulting 333 matches had a squared correlation coefficient r^2 of 0.966 and a standard error of 9.22%.

ScaRaB Comparison

The ARM 0.5° fluxes were averaged into the ScaRaB 2.5° grid. During April 1994, the ScaRaB's precessing METEOR-3 satellite was in a mostly afternoon orbit providing coincident data over a range of SZAs. The data were matched to within ±15 minutes with the same angular restrictions used for original October 1986 regression. Figure 1 shows the resulting scatterplot with the line of perfect agreement. For the 170 matched pixels, the bias is -0.006 and the root mean square (rms) difference is 8.0%.

During July 1994, the ARM GOES analysis was performed only between 38°N and 35.5°N and 99°W and 96.5°W on hourly GOES-7 images because of limited data availability. The individual pixel ScaRaB SWAs were binned into the ARM box, because it does not fit the ScaRaB 2.5° grid. Only the SWAs from July 1-15 were used, because the METEOR-3 was in a near-terminator orbit. The SWAs were matched to within a half hour. No angle restrictions were applied because so few data points are available. The 15 data points (Figure 2) differed by 0.0046, on average, with an rms difference of 10.0%.

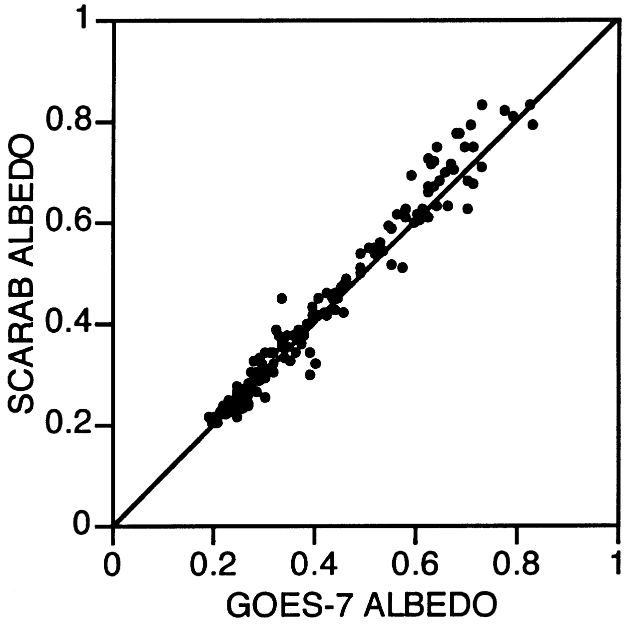

Figure 1. Comparison of ScaRaB and GOES-7 SWA for April 1994.

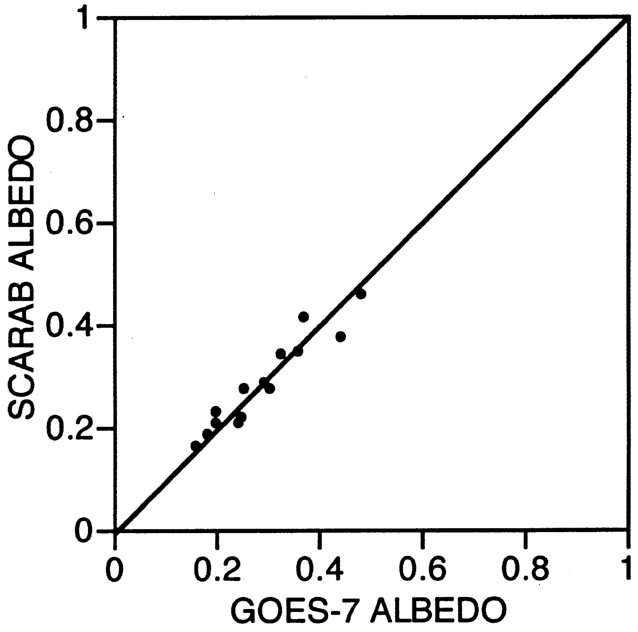

Figure 2. Same as for Figure 1 except for July 1994.

ERBE WFOV Comparisons

The ERBE WFOV has measured fluxes from the ERBS satellite continuously since November 1984 until the present. Those data constitute the longest available time series of single-satellite broadband fluxes. The cavity radiometer has on-board shortwave calibration with a perfect spectral response from 0.2 µm to 5 µm (Smith et al. 1986). The ERBE WFOV has a cosine response function and views earth from limb to limb. Approximately half of the measured energy is contributed by a 10° x 10° latitude-longitude region centered on the sub-satellite point. The ERBE WFOV data are gridded into 10° regions with up to 7 points per region during a given overpass. For comparison with GOES, a minimum of three measurements are required for an overpass. The GOES data were averaged into the 10° region defined by 40°N, 32°N, 100°W, and 91°W and matched in time within the local solar half hour. Table 1 summarizes the differences. The number of samples per month is small, especially during autumn. Except for October 1995 with only five samples, the mean difference is less than 3.0%. Integrating the ARM 0.5° gridded analysis SWA into the ERBE-WFOV footprint and decreasing the coincident time to less than a half hour should improve the results. Given the standard deviations and number of samples, the mean differences are not statistically different from zero. Extending the WFOV study to include other months from 1994 to 1997 should lend more confidence to this validation approach.

Table 1. Comparison of ERBE WFOV and GOES SWA. The bias equals GOES – ERBE WFOV.

Time Period	#	GOES	Bias	Bias %	σ	σ %
3/5 - 5/1/94	16	0.305	-0.004	1.3	0.061	20
10/23-11/15/94	7	0.332	0.005	1.5	0.050	15
9/25-11/1/95	5	0.339	0.022	6.5	0.053	16
4/10-5/10/96	18	0.319	-0.009	2.8	0.070	22

Comparison with Aircraft Data

The TSBR has a hemispherical FOV and a bandpass of 0.224 µm to 3.91 µm. During October 1995, both the Egrett and Otter had up- and downlooking TSBR instruments that are calibrated on the ground and in flight. The Otter and Egrett usually flew coincident flight tracks with the Egrett flying at 13.7 km and the Otter between 1 km and 4 km. SWAs from the TSBR are computed by dividing the up- by the downwelling fluxes. The TSBR fluxes are first summed for each 10-minute leg centered on the GOES-8 image time. The SWAs are then adjusted to the TOA using correction ratios based on computations using the Fu and Liou (1993) radiative transfer model with atmospheric profiles obtained from the CAGEX home page (*http://snowdog.larc.nasa.gov:8081/cagex.html*). The corrections are the ratios of SWA at the TOA to that at aircraft level. The Egrett flew at 13.7 km, so relationships between the flight-level albedo and the correction ratios, CR, were derived for all clear (clr) and cloudy (cld) cases between September 25 to November 1, 1995. Plots of these relationships,

$$CR_{cld} = 1.023 + -0.201\alpha + 0.165\alpha^2, \quad r^2 = 0.94$$

$$CR_{clr} = 1.0050 - 0.0496\alpha, \quad r^2 = 0.40$$

have been presented by Doelling et al. (1997). For the Otter, only clear flight tracks were analyzed and an average correction ratio of 1.035 was used. The 1-km GOES pixels centered on the flight track were averaged over the length of each 10-minute leg to match the TSBR means. Only flight legs that were entirely clear or cloudy within, at least, 10 km around the flight track were used in the comparisons.

Figure 3 shows the results of the Egrett TOA and GOES SWA for both clear and overcast conditions. On average, the GOES SWA is 0.027 greater than that of the Egrett. The rms difference is 0.038, a 14% difference relative to the mean Egrett albedo, 0.271. Under clear conditions, the difference between the Egrett and Otter SWAs is the same as those for the Egrett and GOES (Figure 4) and the results

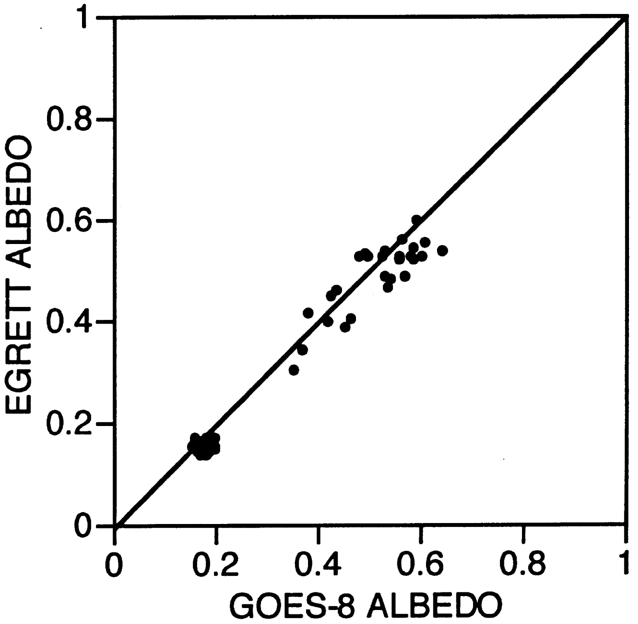

Figure 3. Comparison of Egrett TSBR and GOES-8 SWA for October 1995.

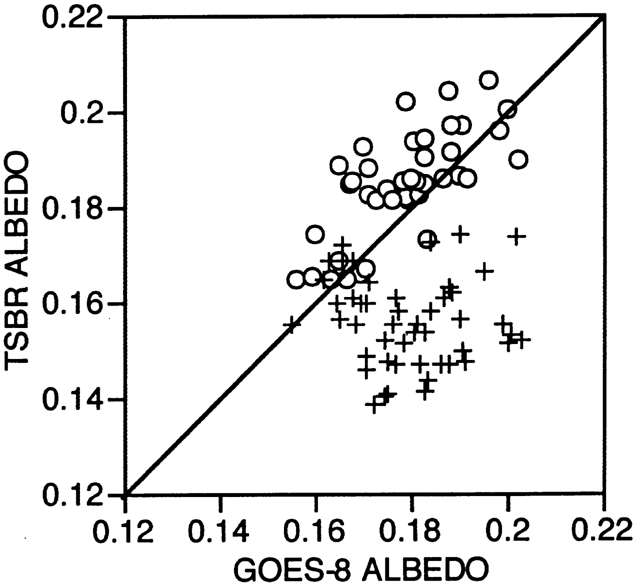

Figure 4. Comparison of Egrett (+) and Otter (O) TSBR and GOES-8 SWA for clear conditions for October 1995.

are displayed in Table 2. The discrepancy between the TSBR fluxes suggests the level of uncertainty in the data for the purpose of validating the high-resolution fluxes from GOES. In this case, the Otter SWAs are closer to the GOES albedos. The differing TOA SWA between the aircraft may be a product of the radiative transfer calculations, especially near the surface in the aerosol layer, where the albedo decreases by more than 0.005. For the surface fluxes to match the TOA fluxes, a more absorbing aerosol layer must be used forcing a change in the Otter correction ratio. The intercalibration of all four aircraft radiometers is also critical and could affect the observed differences. Another uncertainty is the FOV of the TSBR on the Egrett. At 13.7 km, it extends to a radius of 60 km for 95% of the energy. The Otter at 2 km has a radius of 9 km at the same energy level. Weighting each GOES 1-km pixel SWA in the TSBR FOV should reduce the scatter. The actual navigation of each GOES pixel is also uncertain to within a few km and must be checked against natural features. Tests comparing the GOES albedos over the flight tracks to the surrounding larger areas indicate that the GOES navigation and the use of sub-aircraft pixels introduces minimal error into the estimate of the GOES albedo corresponding to the aircraft albedo for both the clear and cloudy cases. The bidirectional models used to convert from radiances to flux may also contribute to the uncertainties. The greatest uncertainties are most likely found in the atmospheric profiles of aerosol and instrument calibration.

Table 2. Differences between aircraft TOA albedos and GOES-8 SWA for clear conditions during October 1995.

Platform	Egrett	Otter
#	49	39
Bias	0.02363	-0.00684
RMS	0.02804	0.01063
RMS %	18.0	5.8
Mean	.1562	0.1848
Ratio	0.9970	1.035

Concluding Remarks

In general, the instantaneous GOES-derived broadband albedos are within ±10% of the various reference albedos and are not biased. This level of agreement is as close as the original data used to derive the narrow- to broadband relationship. That relationship, therefore, can be used confidently for an extended time period over this limited spatial domain. The narrowband to broadband equation assumes that the surface albedo aerosols are the same, on average, from year to year. Comparison of GOES-8 SWA and broadband CERES measurements will be made to ensure that the narrowband to broadband relationship remains valid or requires some updating. Refinements in the relationship can be made using the coincident CERES broadband fluxes and the Visible Infrared Scanner (VIRS) narrowband fluxes on-board the TRMM spacecraft. The VIRS is similar to the AVHRR. Time and angular differences will not be sources of uncertainty. The CERES measurements will enable the development of a complete annual cycle in the relationship which can then be applied to well calibrated GOES data.

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