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Simultaneous spectral albedo measurements near the Atmospheric Radiation Measurement Southern Great Plains (ARM SGP) central facility

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[1] During the second Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE II), measurements were obtained during low-altitude passes of the Twin Otter aircraft directly over the central facility of the ARM Southern Great Plains (SGP) site. One set of measurements taken from this platform was the spectral irradiance pointing in the nadir and in the zenith with moderate spectral resolution from about 350 to 1670 nm using the NASA Ames solar spectral flux radiometer (SSFR). Routine measurements are made at the central facility (CF) of the ARM SGP site using two multifilter radiometer (MFR) heads with six narrowband filters covering portions of the spectrum between 415 and 940 nm. One measures upwelling spectral irradiance above an ungrazed pasture, and the other measures that above a wheat field. In addition, on one of the cloudy days during ARESE II (3 March 2000), measurements were made with a hand-held, commercial spectrometer above wheat, pasture, and dry corn stalks in and around the CF site between the wavelengths of 350 and 2340 nm. A needed input to radiation modeling at the top of the atmosphere and at the surface is the effective spectral surface albedo. In the calculation of downwelling radiation at the surface it is important to correctly specify surface albedo in overcast and clear conditions. This paper will examine the level of agreement among different spectral albedo measurements. The effect of the differences on calculated downwelling surface irradiance will be analyzed for thin and heavy overcast. Finally, the importance of spectral albedo versus a single-valued broadband albedo on modeled, clear-sky diffuse irradiance is demonstrated. *INDEX TERMS:* 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0394 Atmospheric Composition and Structure: Instruments and techniques; 1640 Global Change: Remote sensing; *KEYWORDS:* spectral albedo, downwelling spectral and broadband diffuse irradiance models, aircraft and ground-based spectral albedo comparisons, inhomogeneous spectral albedo

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1. Introduction

[2] A critical input to downwelling, shortwave irradiance models is the effective surface spectral albedo. Because of the variation in surface types around the SGP site, it is difficult to specify an areal-averaged albedo. Figure 6 of *Li et al.* [2002] is a 10 km × 10 km map of surface types that illustrates the complexity of the surface albedo surrounding the CF. In that paper the authors outlined a complex procedure to produce an effective albedo for this site. Landsat ground cover classification maps centered on the CF are used along with surface albedo measurements, taken with a portable spectrometer for a wide variety of land cover types near the CF, to produce an albedo map. An areal-mean albedo is then derived according to cloud height and the Landsat ground cover classification distribution. Spectral models, using these areal-mean albedos as input along with cloud microphysics and cloud location, agree well with spectral irradiance measurements. Inverting the process,

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spectral irradiance measurements and spectral models, with correct cloud input data, are forced to agree by adjusting the spectral albedo for the purpose of retrieving spectral albedo over one annual cycle. In this paper we examine less complex, but effective, methods of measuring spectral albedo.

[3] During ARESE II the Twin Otter aircraft made low-altitude (typically, 100–300 m) passes over the CF at the SGP Clouds and Radiation Testbed (CART) site as part of the flight pattern design for the experiment. The NASA Ames Research Center's solar spectral flux radiometer (SSFR) (P. Pilewskie et al., Cloud solar spectral irradiance during ARESE II, submitted to *Journal of Geophysical Research*, 2003) made frequent and simultaneous zenith-viewing and nadir-viewing irradiance measurements on these flight legs with spectral measurements usually covering the 350–1670 nm wavelength range.

[4] The only routine spectral surface albedo measurements at the CF are two sets of MFR measurements looking down from a 10-m tower situated above ungrazed pasture and looking down from the 25-m level of the 60-m tower situated above a wheat field. These two sites were selected because they represent the two principal surface types in the area surrounding the CF. There are six, nominally, 10-nm wide filters centered near 415, 500, 615, 673, 870, and 940 nm in the MFR heads. There are two multifilter rotating shadowband radiometers (MFRSRs) measuring downwelling spectral irradiance in the central cluster of instruments at the CF using these same wavelengths, thus enabling the calculation of spectral albedo.

[5] On one of the overcast ARESE II measurement days (3 March 2000) handheld spectral measurements were made over wheat field, pasture, and dry cornfield sites near the CF with an Analytical Spectral Devices (ASD) FieldSpec® spectrometer covering the 350–2340 nm wavelength range.

[6] This paper examines the level of agreement among these three measurements. A wavelength parameterization of the MFR albedo measurements is explained. A comparison of spectral and broadband downwelling irradiance calculations is made using the two spectrometer-based albedos and the wavelength-parameterized MFR albedos for optically thin and optically thick clouds. The effect of using a single wavelength-independent albedo versus a measured spectral albedo on calculated downwelling diffuse irradiance is examined for five clear-sky cases.

2. Instrumentation Details

[7] The SSFR, as the name implies, measures spectral flux (irradiance) in the nadir and in the zenith between 350 and 1670 nm with 8–12 nm spectral resolution. The spectrometers were mounted on the Twin Otter aircraft during ARESE II and the data were corrected for pitch, roll, and yaw. For the instantaneous comparisons of the SSFR with ground measurements we used the navigation data from the Twin Otter. The latitude and longitude are recorded to the nearest 0.0001 radian. At cruising speeds near 60 m/sec the navigation system typically had the same latitude and longitude to this precision for about 10 seconds or for about 600 meters of travel. We took the mid point as the time when the aircraft was closest to the central radiometer cluster at the CF.

[8] The MFR measurements made on the 10-m and 25-m towers did not receive frequent calibrations because instruments selected showed good filter stability before deployment. The 10-m tower MFR went two years between calibrations and generally showed less that 10% degradation. We used a linear degradation in time to estimate its calibration during the time of the measurements shown here. The 25-m tower MFR went three years between calibrations. It showed less than 15% degradation in four filters, but 33% and 40% degradation at 415 and 940 nm, respectively. These were corrected assuming a linear degradation in time. The calibration of the downwelling MFRSR used for albedo calculations was checked and found to be consistent with its initial deployment calibration.

[9] The ASD FieldSpec® spectrometer covers the 350–2340 nm spectral range with a spectral resolution between 3 and 10 nm. The unit was used to measure downwelling and upwelling irradiance near the surface in the vicinity of the CF. Green wheat with some visible dark brown soil was observed as was dead pasture grass with no visible soil. Data over a harvested cornfield were also taken, but were not included in the analysis, because this was not considered a major contributor to the CF albedo.

3. Results

[10] Figure 1 is intended to orient the reader to the problem of measuring surface albedo near the SGP CF. It includes no actual measurements from the sight, but it contains data for typical surface types [*Bowker et al.*, 1985] that might be found near the CF. All vegetation in this figure indicates rather low albedo values below about 700 nm that rise sharply to higher values of between 30% and 60% reflectivity in the near infrared and then fall gradually, with some oscillations, at longer wavelengths. Soil reflectivity, on the other hand, rises monotonically from the visible and through a good portion of the near infrared before leveling beyond about 1500 nm. Most of what surrounds the CF is vegetative except during parts of the year when the fields are tilled for planting or when there is snow cover. Therefore, what you might expect for the CF albedo is some composite of albedos similar to these. The amount of radiation reflected depends, of course, on the amount incident. The red curve is a spectrum of total horizontal spectral irradiance in W/m^2-nm for the sun at a solar-zenith angle of 26°. In this case ≈50% of the incident solar radiation is below 700 nm, which reflects poorly from vegetation.

[11] Figure 2 contains albedo measurements made near the CF on the overcast day of 3 March 2000, during ARESE II. The black line is the SSFR albedo measurement at the point when we estimated that the Twin Otter was nearest the central cluster of radiometers based on the navigation data as described earlier. The blue line is the average of all measurements for that particular 5-min flight leg. SSFR measurements above 900 nm were not available for this leg of the flight. The green and red lines were obtained over grass and wheat, respectively, using the ASD hand-held spectrometer. The grass does not show a sharp near-infrared increase because it is dead pasture grass that has not yet started to grow after the winter kill. The red and light blue

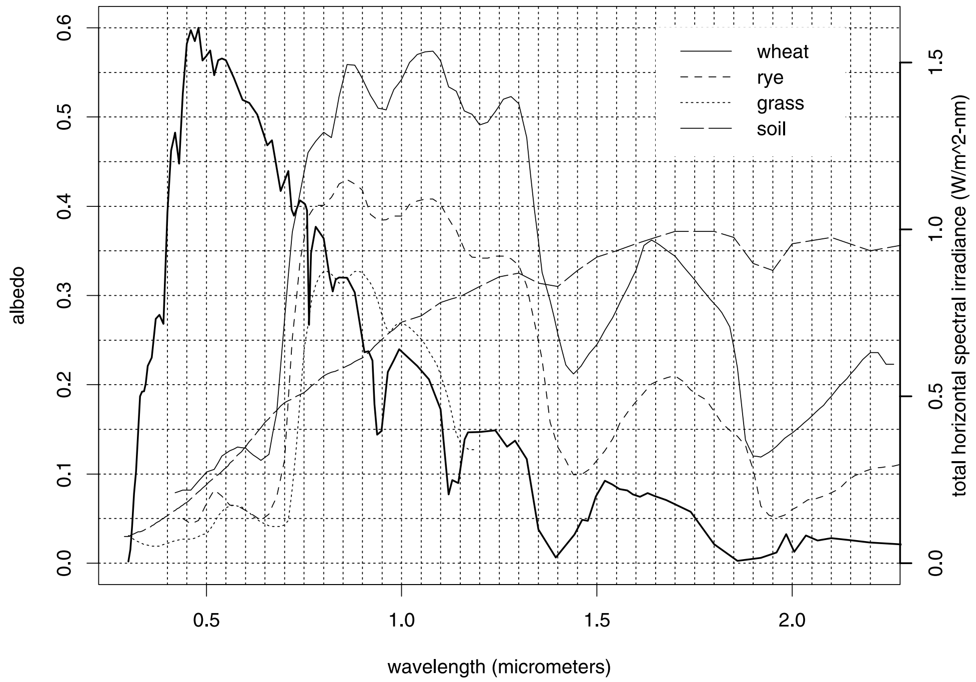

Figure 1. Albedo types that could be found around the SGP CART Central Facility. The red plot is a clear-sky irradiance spectrum (ordinate on the right in red). Clearly much of the shortwave irradiance is in the portion of the spectrum that reflects poorly from vegetation. See color version of this figure in the HTML.

points are MFR measurements from the 25-m and 10-m towers over wheat and dead pasture grass, respectively, ratioed to the measurements of an MFRSR in the central cluster of the CF. These three sets of measurements, over similar surfaces, show the same general behavior with wavelength. The SSFR measurements show a sharp increase near 700 nm suggesting a greater influence of greening vegetation, but slightly less so over the CF than over most of the flight leg (compare blue and black lines).

[12] Figure 3 is a plot of three spectral albedos, based on the data in Figure 2, that were used to calculate the downwelling spectral irradiances for cloud layers of optical

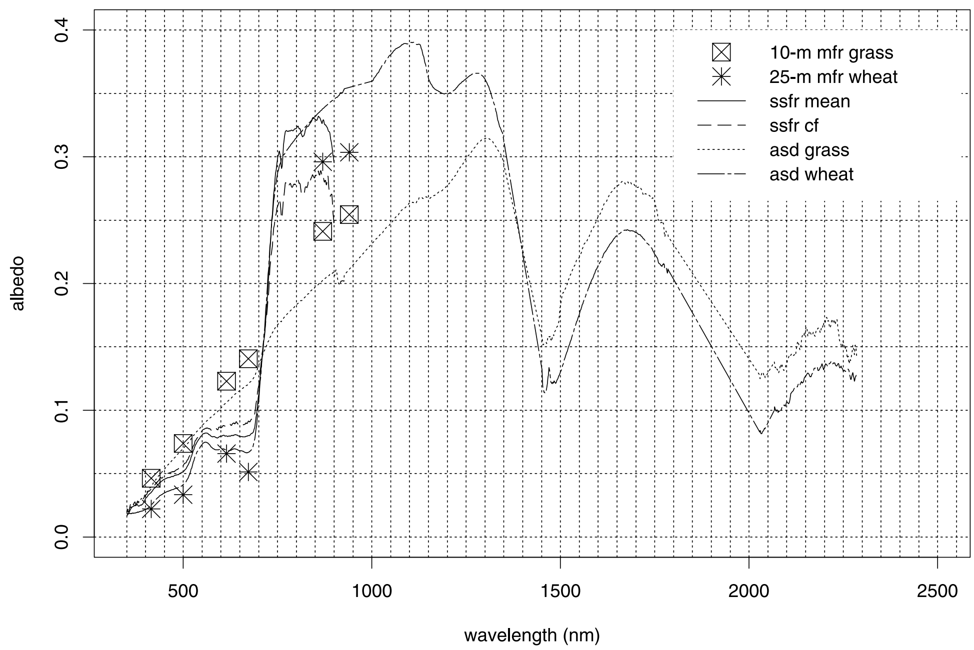

Figure 2. Measured albedos on 3 March 2000. The black ssfr data are assumed to represent the albedo directly over the CF. The blue SSFR data are the averaged albedos from all measurements along a single low-level flight leg. Handheld ASD measurements are red and green lines and the MFR tower measurements are at six specific wavelengths. See color version of this figure in the HTML.

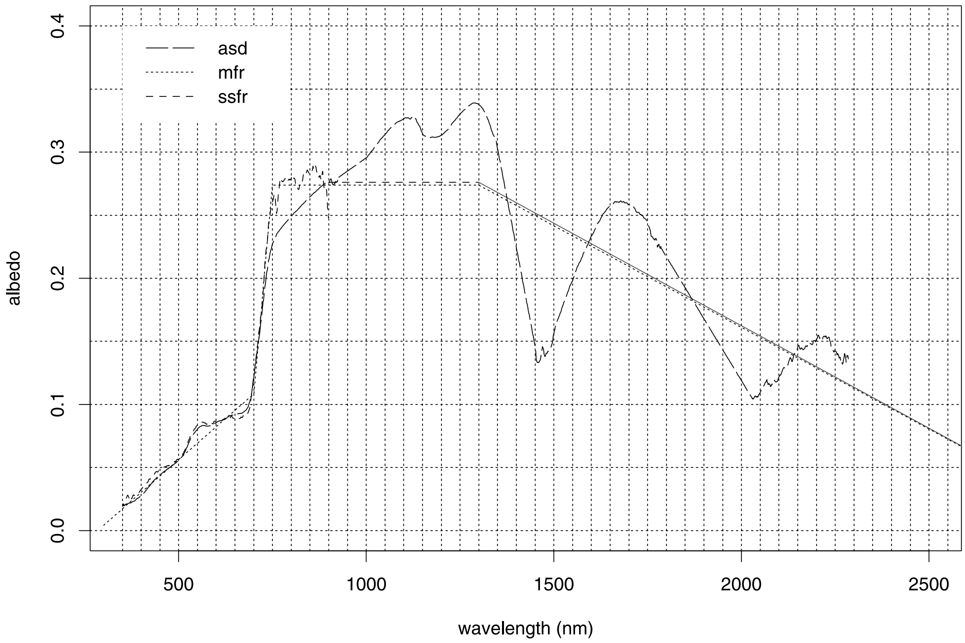

Figure 3. These three curves represent the measured and/or parameterized wavelength dependence of the albedo measurements from different platforms in Figure 2 for input into models. See color version of this figure in the HTML.

depths 5 and 35 in Figure 4. The light blue line in Figure 3 is an average of the ASD wheat and dry pasture albedos. The black line is a combination of SSFR measurements and a parameterization for the rest of the near infrared where we did not have measurements. The average of the data between 750 and 900 nm is taken as a constant albedo from 900 to 1300 nm. From 1300 nm it drops linearly to zero at 3000 nm. The green line is a parameterization using

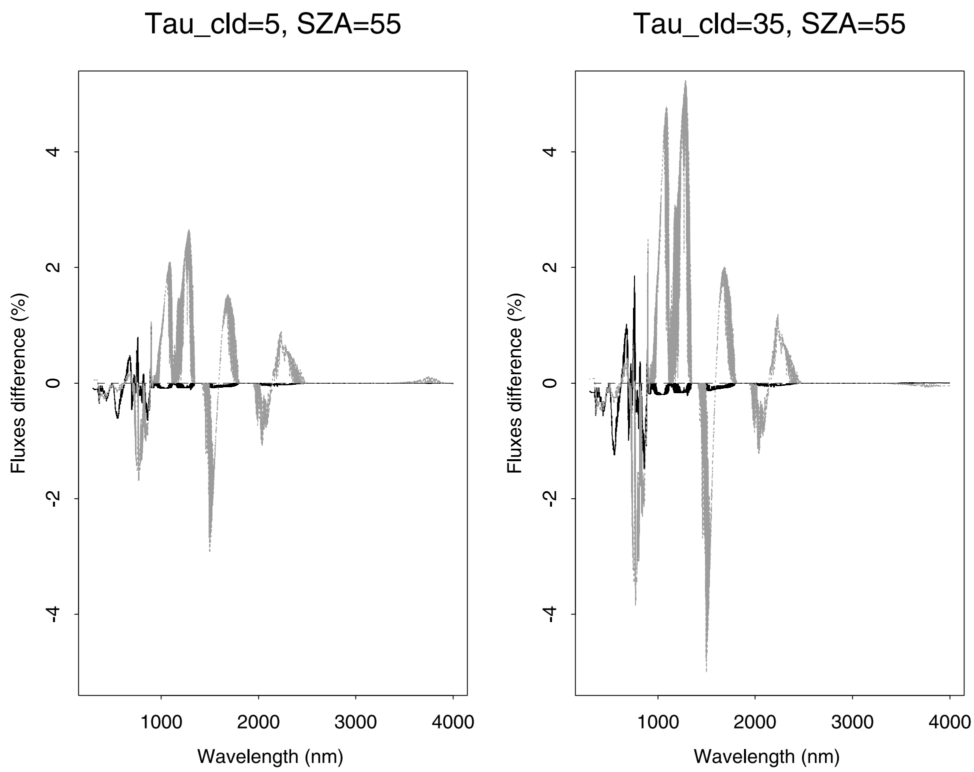

Figure 4. These are the calculated downwelling spectral flux differences using MODTRAN for the ASD albedos (in blue) relative to the SSFR albedos and for the MFR albedos (in red) relative to the SSFR albedos. The spectrally-integrated downwelling irradiance indicated differences of ~0.2% and ~0.1% for either cloud optical depth for the MFR and ASD, respectively. See color version of this figure in the HTML.

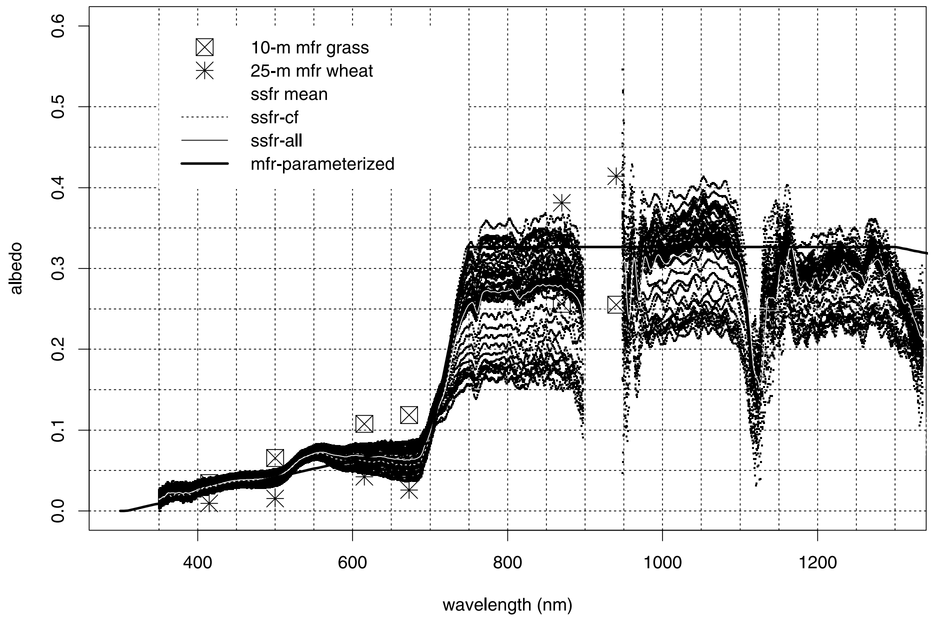

Figure 5. The blue lines are the albedos for each SSFR measurement on another overcast day (29 March 2000) for the low-altitude flight leg. The yellow is the mean and the green is the measurement estimated to be most directly over the CF. Note that the parameterized MFR albedos agree well with the green SSFR measurement for this overcast day as they did for the previous overcast day in Figure 2. See color version of this figure in the HTML.

a straight line fit to the four shortest wavelength filters from both MFRs. A constant based on the average of the two longest wavelength filters from both MFRs is used between 750 and 1300 nm. A linear interpolation connects 700 and 750 nm, and another linear interpolation is used between 1300 nm and an assumed zero albedo at 3000 nm. The 1300 to 3000 nm parameterization is based on the general tendencies of vegetative surface albedos (see Figure 1).

[13] Figure 4 contains results based on MODTRAN calculations of the downwelling spectral irradiance for the three different albedos in Figure 3. In the left of the figure are the differences for a thin cloud layer of optical depth 5, and on the right are the differences for a thick cloud layer of optical depth 35. These model differences in downwelling spectral irradiance are relative to the downwelling spectral irradiance calculated using the SSFR albedo with the ASD difference in blue and the MFR difference in red. The spectral differences are typically less than 5%. Integrated over the shortwave we get broadband irradiance differences of $\sim$0.2% and $\sim$0.1% for both cloud optical depths for the MFR and ASD albedos, respectively.

[14] Figure 5 contains measurements for another overcast day later in the same month (29 March 2000). The dark blue lines are every SSFR measurement in a low-altitude flight leg. Note the significant variation that occurs over a 16-km flight leg. These variations are understandable in the context of Figure 6 of *Li et al.* [2002] that illustrates variability in surface types over a domain of 10 km $\times$ 10 km. The yellow line is the flight-leg average albedo, and the green line is the albedo when the Twin Otter is most nearly over the central cluster of the CF. The MFR measurements for this flight leg are shown as is our parameterization of the six wavelength measurements. In both Figures 2 and 5, which are overcast days, the SSFR measurements closest to the CF are consistent with the curve fits to the MFR measurements. Figure 6 is a plot of the fractional difference in downwelling spectral irradiance calculated using MODTRAN for clouds of optical depth 5 and 35 as was illustrated in Figure 4, but using the parameterized MFR and SSFR-CF measurements of Figure 5 as the albedo inputs. The difference, which is calculated as (SSFR - MFR)/SSFR is typically under 5% spectrally, and the integrated broadband shortwave difference is 0.7% in both cases with the MFR-parameterized albedo yielding slightly higher irradiances.

[15] On 5 April 2000, nine low-altitude legs were flown over the CF. It was a clear day. In Figure 7 we plot the albedos for the five legs for which SSFR measurements were successful and for which, using the procedure described earlier, a near approach to the CF was confirmed. This gives us some idea of the uncertainty associated with our assumption that the mid-point of the CF overpass is our best estimate of albedo from the SSFRs as regards comparison to MFR albedos.

[16] In Figure 8 we plot SSFR and MFR albedo measurements and a MFR parameterization for 5 April 2000. The ssfr-mean albedo is the average albedo for all measurements of one flight leg. The ssfr-cf is the albedo for the measurement made most directly over the CF. The mfr-parameterized albedo is a parameterization of the measurements made with the MFRs and MFRSR at the time of the overpass for this leg. For the cloudy days we had reasonably close correspondence between the SSFR and MFR albedos, but in this figure the SSFR is generally higher than the MFR

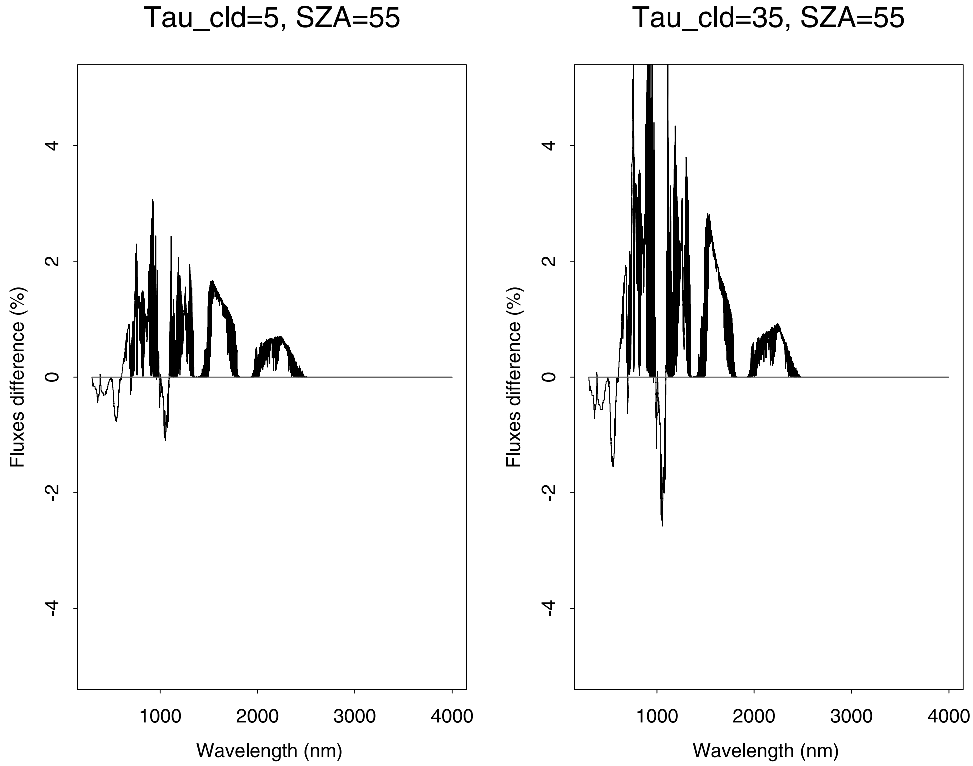

Figure 6. As in Figure 4 these are fractional differences in calculated downwelling fluxes between the MFR-parameterized and SSFR albedos of Figure 5 with the latter taken as the standard for this comparison. For both cloud optical depths the integrated shortwave difference is 0.7%. See color version of this figure in the HTML.

estimates. Figure 9 is a plot of the fractional differences between the downwelling diffuse horizontal irradiance calculated using the SSFR-CF and the parameterized MFR albedos as a function of wavelength. The fractional differences are as large as 6%. The albedos used from Figure 8 are plotted with the scale on the right ordinate axis. The integrated shortwave difference in downwelling diffuse irradiance for this clear day is about 2%.

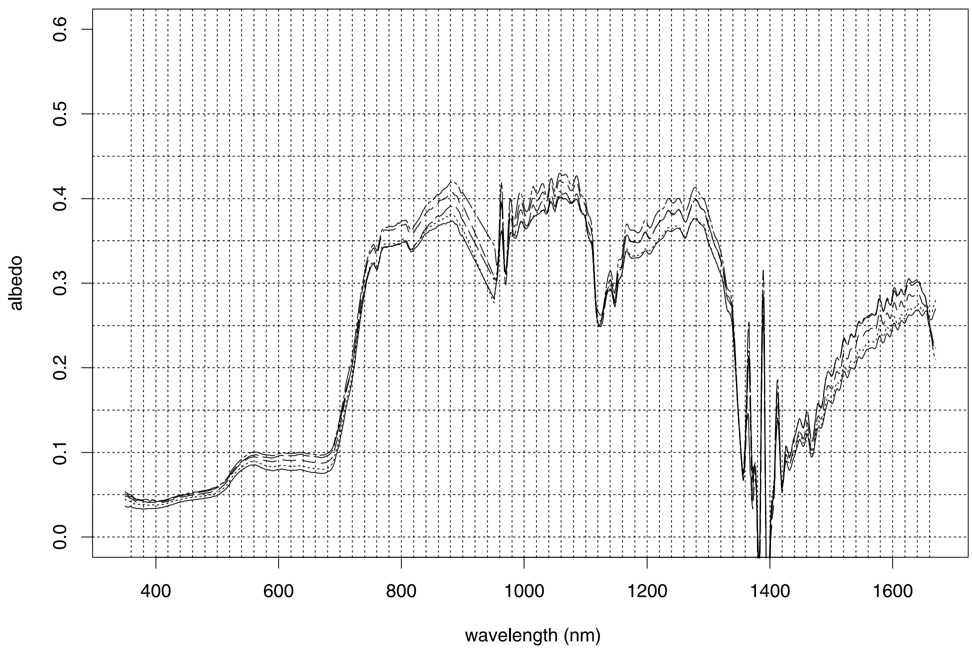

Figure 7. On this clear day (5 April 2000) multiple low-level flight legs were made. The albedos are SSFR measurements when we judged the aircraft to be most directly over the CF. This gives an indication of the reproducibility of these measurements given the uncertainty in the aircraft's exact altitude and location and instrument stability. See color version of this figure in the HTML.

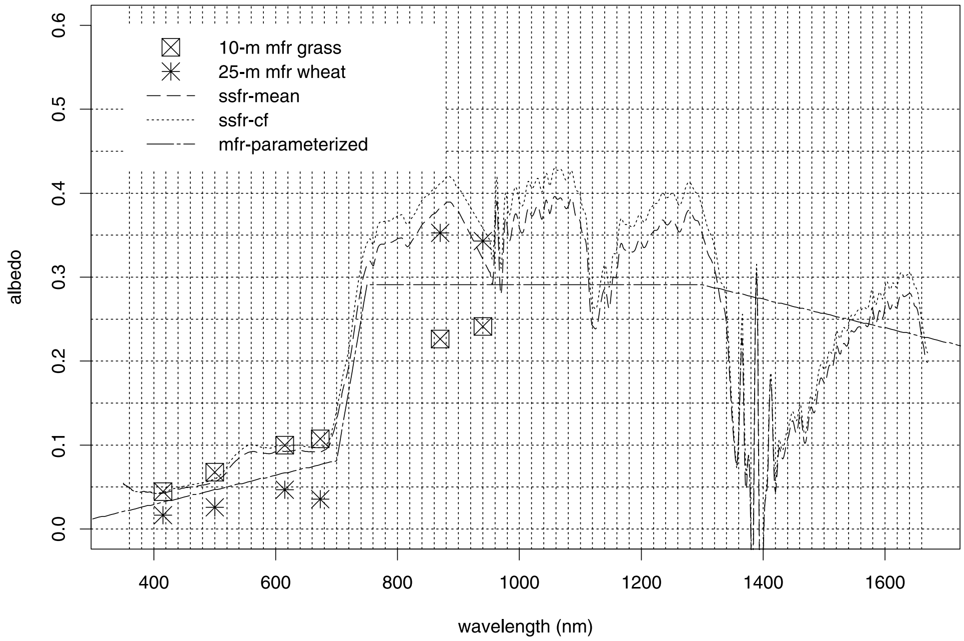

Figure 8. This clear day measurement of albedo demonstrates that the parameterized MFR measurements and SSFR measurements are not always in agreement. This is especially true on clear days. See color version of this figure in the HTML.

[17] Some clear day data, not shown, indicated close agreement similar to the cloudy day data. Still on other days MFRs had higher albedos than the SSFR. We speculate that these differences are associated with the differences in Twin Otter positions, and, therefore, are associated with differences in the scene measured on each pass, or that bi-directional reflectance effects, which are large on clear days because of the large direct solar component, are contributing

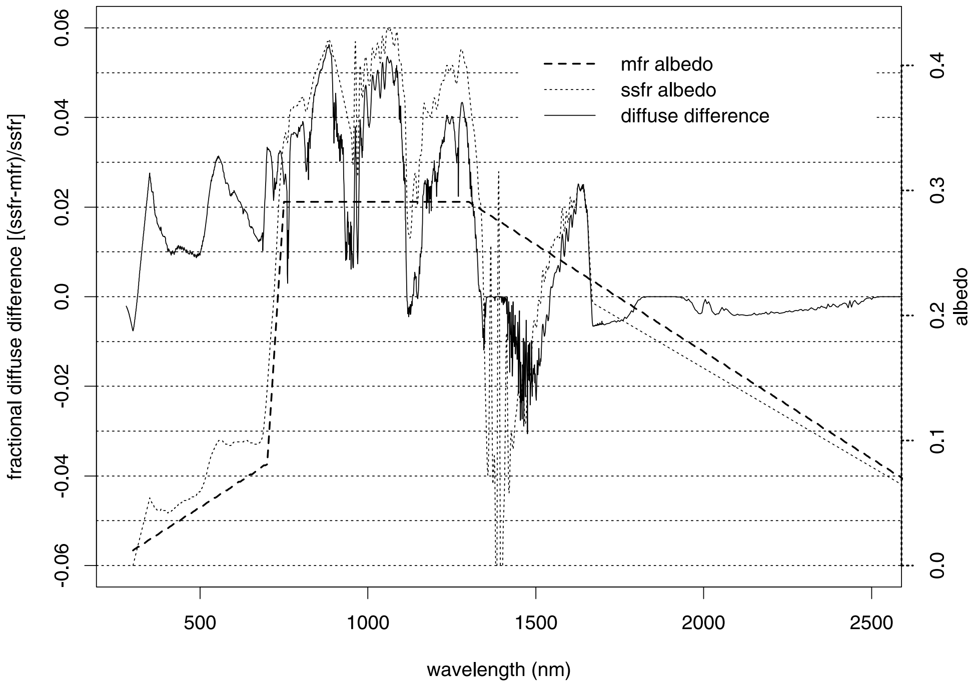

Figure 9. This plot is the fractional difference in diffuse horizontal irradiance produced by the SSFR-CF albedo and the MFR-parameterized albedos of Figure 8. While the fractional differences as a function of wavelength are as high as 6% the integrated shortwave difference is about 2%. See color version of this figure in the HTML.

Table 1. Comparison of Clear Day Measurements and Models Using Measured Spectral and Broadband Albedos

Day (2001)/Local Time	τ_{500}	α	H_2O, cm	Direct, W/m^2 (Model/Measurement)	Diffuse (Spectral Albedo), W/m^2 (Model/Measurement)	Diffuse (Broadband Albedo), W/m^2 (Model/Measurement)
29 Sept/1000	0.102	1.33	1.35	874/877	96/86	100/86
29 Sept/1200	0.103	1.38	1.45	926/924	104/93	109/93
30 Sept/1206	0.091	1.43	1.43	947/943	97/92	103/92
30 Sept/1231	0.100	1.5	1.60	943/944	101/93	107/93
1 Oct/1202	0.087	1.28	1.00	948/947	97/90	102/90

to these differences. On overcast days radiation smoothing apparently minimizes these effects.

4. Summary and Discussion

[18] On the single overcast day where we had all three measurements of albedos, there are differences in the spectral detail as might be expected since we are comparing spot measurements of the handheld ASD spectrometer with the SSFR integrated view flying 200 m above the CF. These spectrally detailed albedos and the parameterized albedo based on the MFR data are used to calculate downwelling spectral irradiance with the result that there are up to 5% differences spectrally that average to $\sim$0.2% or smaller differences in calculated broadband downwelling irradiances even for the optically thin overcast case tested. On a second overcast day we again obtained consistent downwelling irradiances between the SSFR and MFR with a difference that was slightly higher, but still only 0.7%. Since the sample is small we have a suggestion, but no proof that the MFRs provide a reasonable parameterization for downwelling irradiance calculations for overcast conditions.

[19] On the clear day of 5 April 2000 we obtained five estimates of the albedo based on SSFR measurements flying over the CF near solar noon as shown in Figure 7. This demonstrates the uncertainty in our ability to repeat the albedo measurement from the aircraft. Sources of uncertainty include the exact positioning over the same nadir point, the altitude of the measurement, the relative solar position between measurements that determines bi-directional effects, instrument stability, plus other minor contributors. On clear days, not shown, the agreement between the MFR and SSFR measurements varied noticeably within a day and between days, perhaps, because of shifts in positions over a scene, bi-directional effects, or instrument instability. Calculations indicate that even the large differences in SSFR and MFR albedos in Figures 8 and 9 produce downwelling broadband diffuse irradiances on a clear day that only differ by 2%, or about 2 W/m^2. We used the largest albedo of the five obtained from Figure 7 for this calculation of differences. Using the five albedos in Figure 7 to calculate downwelling broadband diffuse irradiance and comparing to the diffuse irradiance calculated using the mfr-parameterized values, we obtained differences that ranged between 1.1% and 2.0%. The largest difference among the calculated downwelling diffuse irradiances using only the five SSFR albedos of Figure 7 was 0.9%.

[20] For downwelling shortwave irradiance modeling, some spectral albedo information (e.g., the parameterized MFR albedos) provides more realistic input to calculations for comparisons to measurements than a constant, wavelength independent albedo measured with a broadband pyranometer. To demonstrate the importance of using a spectral albedo rather than a constant wavelength-independent albedo in downwelling irradiance modeling, we calculated irradiance for five clear-sky cases. The MFR measurements of albedo for 26 September 2001 were parameterized for the 300–3000 nm range using the same procedure as described for the 3 March 2000 data in Figure 3. The measured downwelling broadband irradiance data are from the first ARM diffuse horizontal irradiance comparison, where 14 radiometers simultaneously measured diffuse shortwave irradiance [*Michalsky et al.*, 2003]. The diffuse irradiance measurements in Table 1 are the average of the five most consistent radiometers, and the direct irradiance measurements are obtained with an absolute cavity radiometer. The downwelling diffuse irradiance calculations were repeated using a constant albedo for all wavelengths that was scaled to give the same integrated reflected to integrated downwelling ratio as the spectral albedo. This ensures that we are comparing the effects of using a spectral albedo versus a wavelength-independent albedo, that is, the results are not different because of errors associated with the broadband and spectral albedo measurements.

[21] In Table 1 the aerosol optical depth at 500 nm τ_{500} and the Angstrom exponent α are based on MFRSR measurements at five wavelengths. We assumed an aerosol single scatter albedo and asymmetry parameter of 0.92 and 0.775, respectively. The ozone column as reported by the TOMS satellite was within a couple of Dobson units of 276 DU for the three-day period. The calculations are made with a model by *Gueymard* [1995]. The direct irradiance column indicates excellent agreement between the modeled and measured direct irradiance with differences well within the uncertainties of the measurements of irradiance, the measurements of the inputs to the model, and the model itself. The last column, which uses a fixed, wavelength-independent albedo, contains model and measurement differences that are consistent with the results of *Halthore and Schwartz* [2000]. The next to last column contains results from models that used the measured spectral albedo suggesting that the difference between models and measurements is reduced noticeably by using the spectral albedo.

[22] **Acknowledgments.** Two referees contributed useful comments that strengthened the final version of this paper. The ASD spectrometer field measurements during ARESE II were made with an instrument borrowed from the MISR project team. We especially thank Mark Helmlinger for his assistance. This research was supported by the Biological and Environmental Program (BER), U.S. Department of Energy, grant. DE-FG02-90ER61072.

References

Bowker, D. E., R. E. Davis, M. L. Myrick, K. Stacy, and W. T. Jones, Spectral reflectances of natural targets for use in remote sensing studies, *NASA Ref. Publ.*, *1139*, 1985.

Gueymard, C., SMARTS2, Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and performance assessment, *Rep. FSEC-PF-270-95*, Fla. Sol. Energy Cent., Cocoa Beach, 1995.

Halthore, R. N., and S. E. Schwartz, Comparison of model-estimated and measured diffuse downward irradiance at surface in cloud-free skies, *J. Geophys. Res.*, *105*, 20,165–20,177, 2000.

Li, Z., M. C. Cribb, and A. P. Trishchenko, Impact of surface inhomogeneity on solar radiative transfer under overcast conditions, *J. Geophys. Res.*, *107*(D16), 4294, 10.1029/2001JD000976, 2002.

Michalsky, J. J., et al., Results from the first ARM diffuse horizontal shortwave irradiance comparison, *J. Geophys. Res.*, *108*(D3), 4108, doi:10.1029/2002JD002825, 2003.

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