Comparison of Spectral Direct and Diffuse Solar Irradiance Measurements and Calculations for Cloud-Free Conditions

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Introduction

The comparison of spectral measurements and calculations provides an excellent foundation for analyzing the ability of models to compute the solar irradiance absorbed in the atmosphere. Since molecular absorption bands have distinctive spectral signatures, the absence of an atmospheric absorber in a model would result in spectral measurement-model residuals qualitatively different from those caused by other likely errors. This study presents comparisons between ground-based direct and diffuse irradiance measurements from the Rotating Shadowband Spectroradiometer (RSS) (Harrison et al. 1999) and corresponding multiple-scattering calculations performed by the Code for High Resolution Accelerated Radiative Transfer (CHARTS) (Moncet and Clough 1997). The direct beam residuals alone provide persuasive evidence against the existence of significant unmodeled molecular absorption, with the diffuse irradiance comparisons furnishing effective corroborating information. Additionally, the diffuse irradiance results provide vital information concerning aerosol scattering properties.

Measurement-Model Description

The prototype first-generation RSS used in this study provides measurements of the total horizontal and diffuse irradiance in 512 channels over the frequency interval 9000 cm^{-1} to 28,900 cm^{-1} (1.1 μm to 0.35 μm), with spectral resolution ranging from 91 cm^{-1} in the infrared to 65 cm^{-1} in the ultraviolet. (Due to issues related to detector responsivity, only the data from the spectral region 10,000 cm^{-1} to 28,500 cm^{-1} [1.0 μm to 0.35 μm] is analyzed in this research.) The total and diffuse irradiances are measured through the same optics and by the same detector array, with an automated shadowbanded fore-optic providing the solar beam blocking needed for the diffuse beam measurement.

As shown in Figure 4 of Harrison et al. (1999), extraterrestrial irradiances obtained (via Langley regressions) from RSS measurements based on a standard lamp calibration do not agree in all spectral regions with two commonly used extraterrestrial spectra. Therefore, for this research effort the RSS measured irradiances have instead been calibrated to the values of the Kurucz solar source function (SSF) (1992), which is employed by the radiative transfer models (RTM) used in this study, thereby preventing the generation of spurious spectral features in the comparison. In the assessment of the measurement-model agreement for the direct and diffuse irradiances, this scaling of the RSS measurements greatly reduces the effect of systematic instrument calibration issues and SSF inaccuracies. With the scaling, the comparison is effectively between measured and modeled atmospheric transmittances, although it is performed in the domain of surface irradiances.

The numerically accurate CHARTS multiple-scattering model was developed to extend the capabilities of the line-by-line RTM (LBLRTM) (Clough et al. 1992) to the treatment of clouds and aerosols. The model, which assumes plane-parallel atmospheres, makes use of monochromatic gaseous optical depths computed by LBLRTM and an accelerated adding/doubling scheme. For the irradiance calculations presented here, 12 computational streams were used in a manner that accounted for the instrument's cosine response.

All of the measurements that are considered in this paper were taken with the RSS at the Southern Great Plains Atmospheric Radiation Measurement Cloud and Radiation Testbed (SGP ARM CART) site. The atmospheric profiles used for the calculations are obtained in a similar manner to those used for measurement-model comparisons in the longwave (Brown et al. 1998). As in the longwave calculations, the water vapor profiles are from temporally coincident radiosonde measurements that have been scaled to agree in total column amount with the CART microwave radiometer. The ozone profiles are from climatology scaled to agree with the total column amount measured by the Total Ozone Mapping Spectrometer (TOMS). The most recent spectroscopic parameters for water vapor lines, corrected as in Giver et al. (2000), and the CKD water vapor continuum (Clough et al. 1989) were employed. All important known sources of solar beam attenuation were accounted for, including absorption by molecular oxygen (Greenblatt et al. 1990).

Results

The red curve in Figure 1a shows the results of the direct-beam measurement taken under cloud-free skies on October 2, 1997, at 11:32 am (local time), corresponding to a solar zenith angle (SZA) of 41.8° (2.7 cm of water vapor in the vertical path). A monochromatic calculation of the direct-beam irradiance by LBLRTM was performed for the atmospheric conditions at that time, but without accounting for attenuation by aerosols. The RSS instrument (slit) function was applied to the calculated irradiances, yielding a value of irradiance corresponding to each spectral channel of the instrument. Aerosol extinction was then accounted for by fitting an Angstrom relation to the values of $-\ln(I_{RSS}/I_{LBLRTM})$ at more than 30 spectral points located throughout the RSS-measured domain and characterized by the relative lack of molecular absorption. As shown in Figure 2, the aerosol optical depths obtained by this procedure are within 0.01 of the average of the aerosol optical depths measured by colocated sun photometers (Schmid et al. 1999). The result of applying the spectrally-varying aerosol extinction to the LBLRTM-calculated irradiances is shown in the green curve in Figure 1a. The differences between the

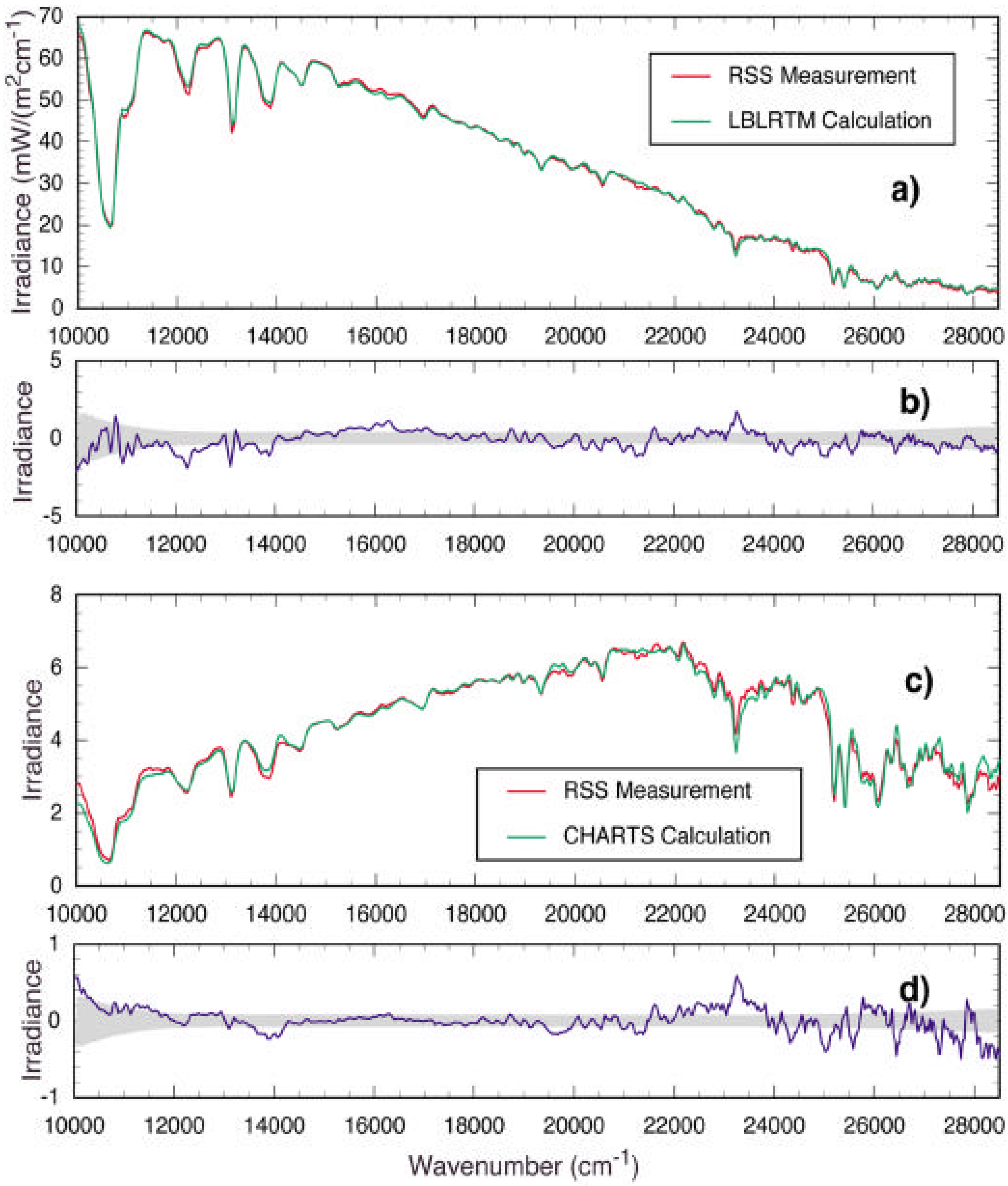

Figure 1. October 2, 1997 case (1.3 airmasses; 2.7 cm vertical PWV): a) Direct-beam spectral irradiances; b) direct-beam differences (RSS-LBLRTM); c) diffuse spectral irradiances; d) diffuse differences (RSS-CHARTS).

measured and calculated irradiances, shown in Figure 1b, are small across most of the measured spectrum. (The shaded region in Figure 1b and other residual plots in this paper represents the confidence limit for the result.) The residuals in the region near 12000 cm^{-1} (0.83 µm) indicate that the model does not have enough absorption in this water vapor band, most likely due to missing lines in the

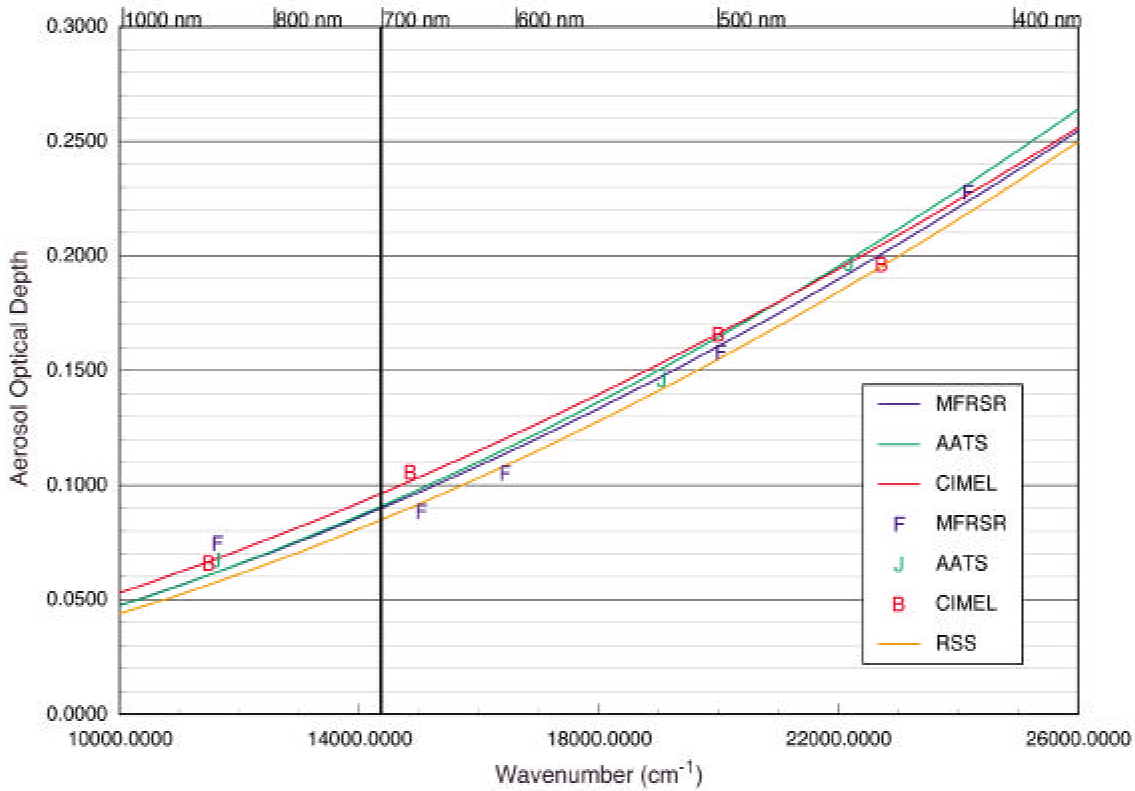

Figure 2. Aerosol Optical Depths from Measurements on October 2, 1997.

spectroscopic database. The slope of the residuals between 16000 cm^{-1} and 22000 cm^{-1} (0.63-0.45 μm) indicates that the fitted Angstrom exponent, influenced by the residuals in the near-infrared, is not optimal for this spectral range.

The aerosol optical depths derived from the direct-beam comparison, together with molecular and Rayleigh optical depths, are used for the calculation by CHARTS of the diffuse irradiances. Also used for the calculation are spectrally-dependent values of surface albedo derived from on-site measurements taken by a Multi-Filter Rotating Shadowband Radiometer (MFRSR). Due to the absence of measurements concerning the spectral dependence of the aerosol asymmetry factor (g) and single-scattering albedo (ω), spectrally-independent values for each were used in the CHARTS calculation. Based on similar previous studies of aerosols at the CART site in Oklahoma (Kato et al. 1997; Halthore and Schwartz 2000), a value of g=0.7 was employed. For the single-scattering albedo, it was found for this case that a value of ω=0.89 resulted in relatively small differences between the measured and calculated spectral diffuse irradiances. The result of this scattering calculation is shown in Figure 1c along with the diffuse irradiances measured by the RSS. The spectral differences between the measurement and calculations are shown in Figure 1d and indicate good agreement throughout the majority of the spectral domain of the instrument.

The direct and diffuse results from this case are summarized in Table 1, as are the results from the two other cases analyzed below. Also included in this table are estimates of the uncertainties (at 80% confidence level) associated with each of the measured and calculated physical quantities. For the RSS irradiance values listed we have assumed an accuracy of 1%, and an instrumental precision of 1% was assumed in the computation of the uncertainties associated with the irradiance residuals.

Table 1. Summary of cases analyzed.

			Precipitable Water Vapor (cm)		Direct-Normal Irradiance, W/m^2			Diffuse Irradiance, W/m^2			Aerosol Properties Used in Calculations		
Case	Time	SZA	Vertica	Path	RSS(u)	LBLRTM(u)	Residuals(u)	RSS(u)	CHARTS(u)	Residuals(u)	Optical Depth(u)*	Angstrom Exponent(u)	Single-Scattering Albedo(u)
October 2, 1997	17:32	41.8	2.7	3.5	637.6 (6.4)	640.2 (1.8)	-2.6 (6.6)	82.2 (1.3)	83.8 (1.5)	-1.6	0.084 (11)	1.82 (20)	0.85 (05)
September 18, 1997	23:28	77.7	4.2	19.2	306.8 (3.1)	308.9 (0.7)	-2.2 (3.2)	44.9 (1.1)	46.4 (0.6)	-1.5	0.375 (10)	1.45 (04)	0.85 (02)
September 29, 1997	17:26	41.2	1.4	1.8	700.9 (7.0)	702.9 (0.6)	-2.0 (7.0)	52.5 (1.1)	53.6 (0.4)	-1	0.036 (10)	1.06 (33)	0.60 (10)

Irradiances correspond to spectral range 10,000 cm^{-1} to 28,500 cm^{-1} (0 µm to 0.35 µm).
u = uncertainty in associated quantity.
* Evaluated at 14,286 cm^{-1} (0.7 µm).
† Asymetry parameter = 0.7.

A second analysis was performed using the RSS measurement taken on September 18, 1997, at 5:30 pm. This case is notable due to its associated high water vapor column amount (4.2 cm) and large SZA (77.8°), resulting in 19.2 cm of water vapor in the direct-beam path. The measured and calculated direct-beam irradiances are shown in Figure 3a; with the aerosol extinction determined using the same method as above. As before, the aerosol optical depths determined using the RSS observations are consistent with those obtained using sun photometer measurements. The differences between the measured and computed irradiances are shown in Figure 3b and indicate good agreement. For a case characterized by such a high water vapor path amount, this result is of particular interest in light of recent conjectures concerning the role of water vapor absorption in explaining measurement-model discrepancies (Arking 1996; Arking 1999). Figure 3c shows the RSS measurement and the corresponding calculation by CHARTS (single-scattering albedo = 0.90) of the diffuse irradiance. The spectral behavior of the diffuse differences shown in Figure 3d, although indicating a need for moderate spectral dependence of the aerosol single-scattering albedo, corroborate the evidence in Figure 3b that there is no unmodeled molecular absorption for this case.

Figure 4 presents the results corresponding to the RSS measurement of September 29, 1997, at 11:26 am (41.2° zenith angle; 1.4 cm vertical water vapor). For this case, the scattering calculation by CHARTS employed an aerosol single-scattering albedo of 0.67. The residuals shown in Figures 4b and 4d are consistent with the other two cases analyzed and indicate good agreement between the measurement and the calculations.

Discussion

The comparisons shown above between the direct and diffuse RSS measurements and CHARTS calculations provide persuasive evidence that there is no unknown molecular absorption of significance in the spectral range of the RSS. It is important to note that this result is independent of the instrument used to

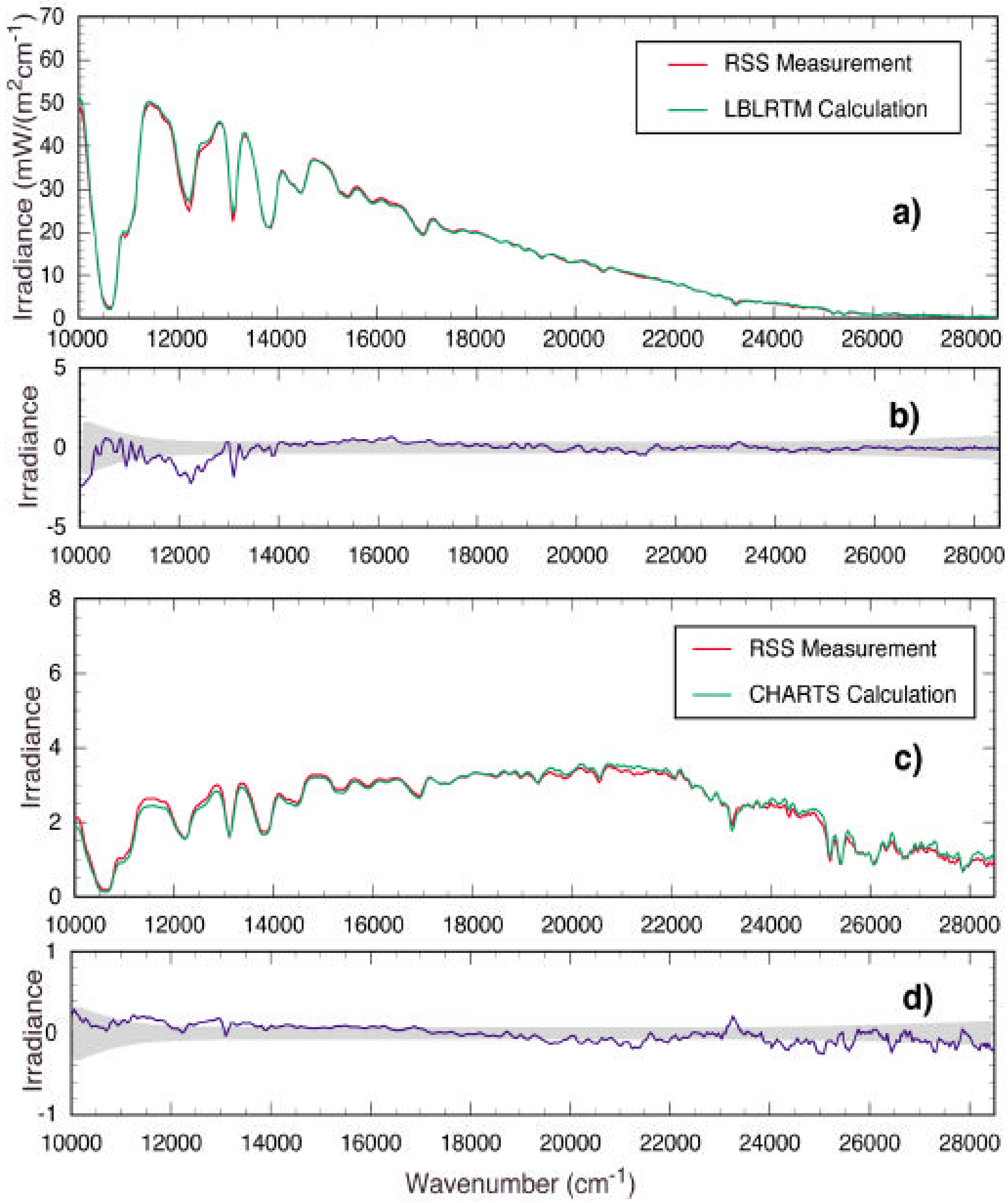

Figure 3. September 18, 1997 case (4.6 airmasses; 4.2 cm vertical PWV): a) Direct-beam spectral irradiances; b) direct beam differences (RSS-LBLRTM); c) diffuse spectral irradiances; d) diffuse differences (RSS-CHARTS).

determine the aerosol optical depths. Based on the results of this study, comparisons done between direct-beam measurements and calculations for the spectral range 3000 cm^{-1} to 10,000 cm^{-1} (3.3 µm to 1.0 µm) (Brown et al. 1999), and extensive high-resolution measurement-model comparisons in the longwave (550 cm^{-1} to 3000 cm^{-1} [18.2 µm to 3.3 µm]) (Brown et al. 1998), it can be concluded that state-of-the-art RTMs accurately account for atmospheric absorption between 550 cm-1 and 28500 cm^{-1} (18.2 µm and 0.35 µm).

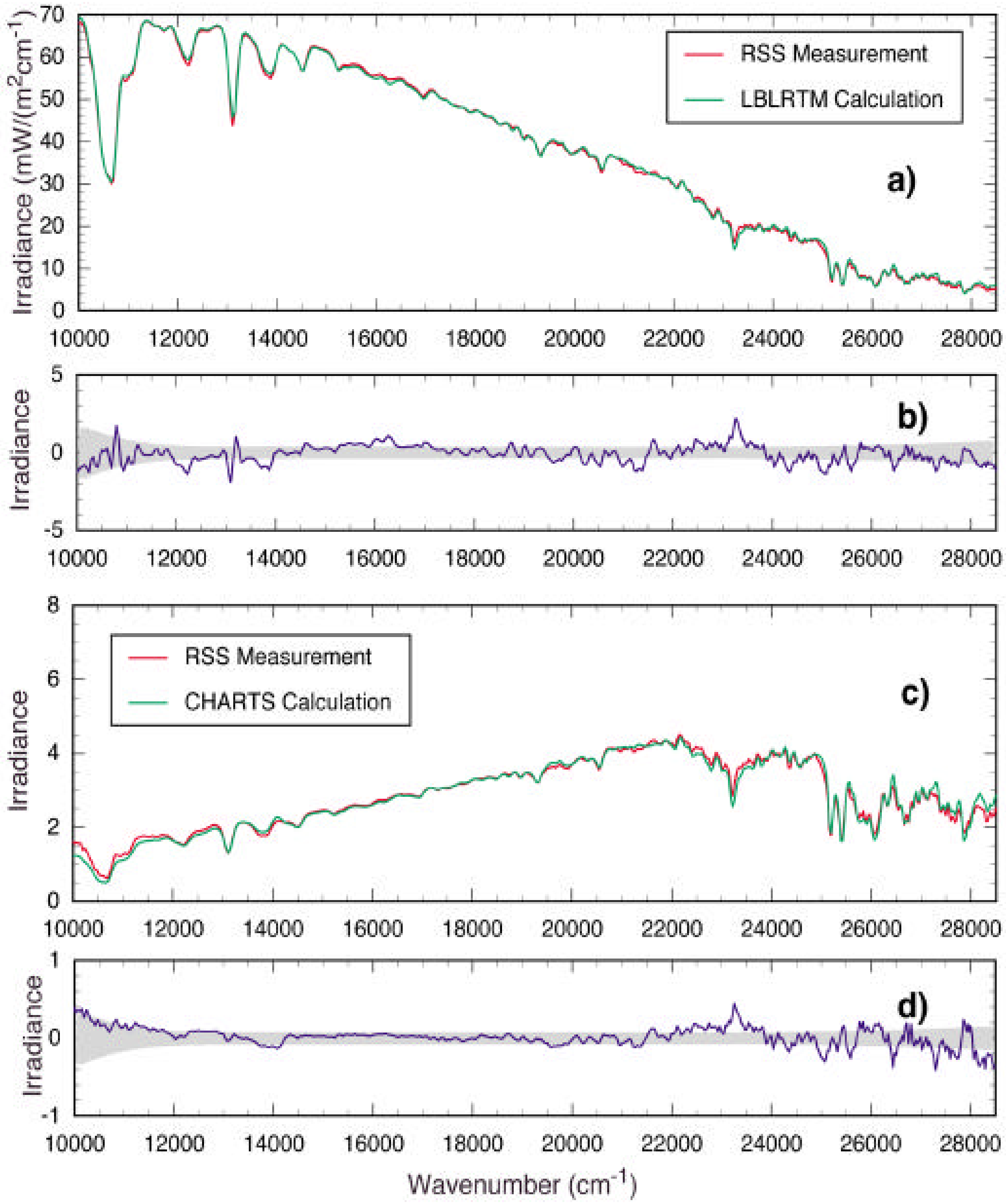

Figure 4. September 29, 1997 case (1.3 airmasses; 1.4 cm vertical PWV): a) Direct-beam spectral irradiances; b) direct-beam differences (RSS-LBLRTM); c) diffuse spectral irradiances; d) diffuse differences (RSS-CHARTS).

Instead, the results of this study suggest that the most likely cause of the unexplained discrepancies between measurements and calculations reported in previous studies is the use of aerosol single-scattering albedoes that are too large (Kato et al. 1997; Pilewskie et al., 2000; Halthore and Schwartz 2000). Evidence for this can be seen in the cases in common between this work and those presented in Halthore and Schwartz (2000). The use of single-scattering albedoes determined as described above would substantially reduce the reported discrepancies in the corresponding cases in this other study.

Table 2 presents both the single-scattering albedo measurements and values inferred from the RSS-CHARTS comparisons (as described above) corresponding to two days in autumn 1997 characterized by relatively low values of single-scattering albedo. As can be seen, the single-scattering albedos needed for agreement between the diffuse RSS measurements and CHARTS calculations are lower than the corresponding measured values, although the combined uncertainties in the measured and retrieved single-scattering albedos are greater than the associated differences. When the asymmetry parameter values of 0.7 used in the calculation are replaced by the measured values from Halthore and Schwartz (2000), the differences between the measured and inferred single-scattering albedo values are far less than the uncertainties. Whether these differences in single-scattering albedos are due to systematic errors in the measurements and/or the methodology described above is an area of active investigation.

Table 2. Cases Associated with Low Single-Scattering Albedos (9/27/97: PWV ≅ 2.7 cm; AOD (700 nm) ≅ 0.04; 9/29/97: PWV ≅ 1.4 cm; AOD (700 nm) ≅ 0.03).

Source of SSA Value	Date	Time (UT)	SSA	Uncertainty
RSS/CHARTS (with g=0.7)	9/27	17:24	0.76	0.09
RSS/CHARTS (with g=0.6*)	9/27	17:24	0.80	0.09
RSS/CHARTS (with g=0.7)	9/27	20:25	0.77	0.09
RSS/CHARTS (with g=0.6*)	9/27	20:25	0.81	0.09
Surface Nephelometer/PSAP*	9/27	14:20	0.86	0.05
Surface Nephelometer/PSAP*	9/27	17:24	0.86	0.05
Aircraft Nephelometer/PSAP (0 km to 1.0 km)[†]	9/27	16:00 to 18:00	0.86	0.05
Aircraft Nephelometer/PSAP (1.0 km to 2.0 km)[†]	9/27	16:00 to 18:00	0.86	0.05
Aircraft Nephelometer/PSAP (2.0 km to 3.0 km)[†]	9/27	16:00 to 18:00	0.88	0.05
RSS/CHARTS (g=0.7)	9/29	17:26	0.67	0.12
RSS/CHARTS (g=0.5*)	9/29	17:26	0.73	0.12
Surface Nephelometer/PSAP*	9/29	14.33	0.76	0.05
Surface Nephelometer/PSAP*	9/29	20:22	0.83	0.05
Surface Nephelometer/PSAP*	9/29	23:24	0.79	0.05
Aircraft Nephelometer/PSAP (0 km to 1.5 km)	9/29	18:30-20:30	0.84	0.05

PSAP - particle soot absorption photometer.
* From Halthore and Schwartz (2000).
[†] From Kato et al. (2000).

The values of single-scattering albedo used in this work, especially for the September 29, 1997, case, are lower than the aerosol single-scattering albedoes usually assumed in the aerosol community for this location, and present an intriguing puzzle for this community to consider. In addition, the values are less than the range of values typically employed in global climate models and represent a potentially substantial source of unmodeled atmospheric absorption.

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