Comparison of spectral direct and diffuse solar irradiance measurements and calculations for cloud-free conditions

Eli J. Mlawer, Patrick D. Brown, Shepard A. Clough
Atmospheric and Environmental Research, Inc., Cambridge, Massachusetts

Lee C. Harrison, Joseph J. Michalsky, Piotr W. Kiedron
Atmospheric Sciences Research Center, State University of New York, Albany

Tim Shippert
Pacific Northwest National Laboratories, Richland, Washington

Abstract. Ground-based spectral measurements of direct and diffuse solar irradiance from the Rotating Shadowband Spectroradiometer, taken in cloud-free conditions in Oklahoma in the fall of 1997, are compared over the spectral range 10000-28500 cm^{-1} to corresponding calculations by an accurate multiple-scattering radiative transfer model. For each case analyzed, the aerosol optical depths used in the calculation were determined by fitting an Angstrom relation based on the ratio of the direct-beam measurements to a direct-beam calculation with no aerosols present. A spectrally-invariant aerosol single-scattering albedo was used in the multiple-scattering calculation, with its value chosen to provide agreement with the diffuse-beam measurements. The spectral agreement between the measurements and calculations for both the direct and diffuse beams is very good, providing strong evidence that there are no unmodeled molecular absorbers of any significance in the atmosphere in this spectral range. Especially notable is the correspondence between the observations and calculations for a case characterized by a large amount of water vapor in the direct-beam path, directly contradicting the suggestion that water vapor absorbs more shortwave radiation than is represented in radiative transfer models.

Introduction

Absorption of solar radiation by the atmosphere is a critical component of the energy balance of the earth and a key factor in the evolution of its climate. Gases and aerosols are responsible for much of this absorption, making the understanding of the deposition of solar energy in cloud-free conditions essential to our knowledge of the earth's radiation budget. Recent studies [Kato et al., 1997; Halthore et al., 1998] have questioned the accuracy of radiative transfer model calculations of clear sky solar flux. These studies found that measurements and model calculations of solar irradiance were in disagreement, and speculated that an unmodeled absorbing gas might be the source of this discrepancy. These studies were based on comparisons between surface broadband observations and calculations, which limited their ability to verify this hypothesis. Other research [Arking, 1996; Arking, 1999; Pilewskie et al., 2000] has sought to determine the source of the disagreement by the use of a regression analysis to explore the dependence of measurement-model irradiance differences on a number of atmospheric state parameters. Some of these works have suggested that absorption by water vapor is not sufficiently represented in radiative transfer models. These studies were also done using broadband data, making it difficult to separate the effects of water vapor amount and aerosol optical depth, which have been found to be correlated for the cases involved [Arking, 1999].

The comparison of spectral measurements and calculations provides a superior 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 in the comparison, such as instrument calibration and aerosol modeling. It is important to emphasize that spectral residuals consistent with inaccurate modeling of molecular

absorption would be detectable even if there are inaccuracies with limited spectral content caused by these other factors.

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 are able to provide persuasive evidence concerning the possible existence of unmodeled molecular absorption, with the diffuse beam residuals furnishing effective corroborating information. Further examination of the RSS-CHARTS direct-beam residuals, plus similar analyses of measurement/model comparisons based on direct-beam measurements from 3000-10000 cm^{-1} (3.3-1.0 μm) by the Absolute Solar Transmittance Interferometer (ASTI) [Murcray et al., 1996], are presented in a companion paper [Mlawer et al., 2000].

Measurement-Model Description

The RSS provides measurements of the total horizontal and diffuse irradiance in 512 channels over the frequency interval 9000-28900 cm^{-1} (1.1-0.35 μm), with spectral resolution ranging from 91 cm^{-1} in the infrared to 65 cm^{-1} in the ultraviolet. The spectral range of the instrument includes ~70% of the incoming solar energy. (Due to issues related to detector responsivity, only the data from the spectral region 10000-28500 cm^{-1} (1.0-0.35 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 occultation needed for the diffuse beam measurement. The horizontal direct-beam irradiance is obtained by differencing the total and diffuse measurements, and is then converted to a direct-normal irradiance. The instrument is calibrated on site to a precision of 1% using Langley analysis. The RSS

measurements are related to an absolute calibration standard using a portable LI-COR lamp.

As shown in Figure 4 of Harrison et al. [1999], extraterrestrial irradiances obtained from RSS measurements (via Langley regressions) that use the LI-COR absolute reference calibration do not agree in all spectral regions with commonly used extraterrestrial spectra. Therefore, for this research effort the RSS measured irradiances have instead been referenced to the values of the Kurucz solar source function [1992], which is employed by the radiative transfer models used in this study, thereby preventing the generation of spurious spectral features in the comparison. The choice of scaling the RSS measurements instead of the solar source function values does not imply absolute confidence in the Kurucz values, but, instead, recognizes the challenges involved in the calibration of shortwave instruments [Kiedron et al., 1999].

The numerically accurate CHARTS multiple-scattering model was developed to extend the capabilities of the line-by-line model 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 performs calculations using the adding/doubling scheme. For the calculations presented in this work, 12 computational streams were used.

All of the measurements that are considered in this paper were taken by the RSS at the Southern Great Plains Cloud and Radiation Testbed (CART) site of the Atmospheric Radiation Measurement (ARM) [Stokes and Schwartz, 1994] Program, located in Lamont, Oklahoma. 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; Clough et al., 2000]. 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. Also included in the calculations are Rayleigh scattering and absorption by molecular oxygen.

Results

A series of observations were taken by the RSS in fall 1997 under cloud-free skies at the ARM CART site. The red curve in Figure 1a shows the results of the direct-beam measurement obtained on October 2, 1997 at 11:32 am (local time), corresponding to a solar zenith angle 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 function was applied to the calculated irradiances, yielding a value of irradiance corresponding to each spectral channel of the instrument. Due to the lack of aerosol extinction in the model, the ratios between the measured and calculated irradiances are less than unity. 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. The aerosol optical depths obtained by this procedure have been found to be in good agreement with those obtained from Angstrom relations derived from colocated measurements by both the Multi-Filter Rotating Shadowband Radiometer (MFRSR) and a CIMEL sun photometer [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 measured and calculated irradiances, shown in Figure 1b, are small across most of the measured spectrum. (The

shaded region in Fig. 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 spectroscopic database. In addition, the spectral residuals near 23000 cm^{-1} (0.43 μm) demonstrate a probable issue in the modeling of the H_γ line in the Kurucz solar source function for this case.

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-beam irradiances. For this calculation, spectrally-varying values of surface albedo obtained by on-site measurements taken by the MFRSR were used. Due to the absence of measurements concerning the spectral dependence of the aerosol asymmetry factor (g) and single-scattering albedo (ω), spectrally-invariant 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=0.85 resulted in relatively small differences between the measured and calculated spectral diffuse irradiances. The result of this multiple-scattering calculation is shown in Figure 1c (the corresponding direct-beam irradiance calculation by CHARTS was consistent with that of LBLRTM) 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 mentioned 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.

Table 1. Summary of Cases Analyzed

Case	Time	Solar Zenith Angle	Precipitable Water Vapor, cm		Direct-normal Irradiance, W/m²			Diffuse Irradiance, W/m²			Aerosol Properties Used in Calculations†		
			Vertical	Path	RSS(u)	LBLRTM(u)	Residuals(u)	RSS(u)	CHARTS(u)	Residuals	Optical Depth(u)*	Angstrom Exponent(u)	Single-scattering Albedo(u)
October 2, 1997	17:32 Z	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 Z	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 Z	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 10000-28500 cm^{-1} (1.0-0.35 mm)
u - uncertainty in associated quantity
*evaluated at 14,286 cm^{-1} (0.7 mm)
†asymmetry 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 solar zenith angle (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 2a, 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 2b and are in 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 model-measurement discrepancies [Arking, 1996; Arking, 1999]. Two of the more apparent features in Figure 2b, at 15800 cm^{-1} (0.63 μm) and 17300 cm^{-1} (0.58 μm), are due to O_2-O_2 collision complexes [Greenblatt et al., 1990], which are absent from the model calculations. Figure 2c shows the diffuse-beam RSS measurement and the corresponding irradiance calculation by CHARTS (using a single-scattering albedo of 0.85). The spectral behavior of the diffuse differences shown in Figure 2d, although indicating a possible need for some spectral dependence of the aerosol single-scattering albedo, corroborate the evidence in Figure 2b that there is no unmodeled molecular absorption for this case.

Figure 3 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 0.60. The residuals shown in Figures 3b and 3d 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. By themselves, the lack of spectral features resembling absorption bands in the direct beam residuals argues convincingly against the possibility of missing molecular absorbers. It is important to note that this result is independent of the instrument used to determine the aerosol optical depths. Although unlikely, an argument can be made that the existence of an unmodeled molecular absorber of significance could be masked by the Angstrom relation that determines the spectral dependence of the aerosol optical depths, leaving no trace in the direct beam residuals. In principle, this could occur if the unmodeled molecular absorbing feature were located in one of the spectral regions used to determine the Angstrom coefficients. In that case, however, the resulting aerosol optical depth would be in error, likely leading to the generation of substantial diffuse beam residuals near the spectral region affected. The lack of such a spectral signature in the diffuse residuals examined in this work corroborates the conclusion from the direct-beam comparisons that there are no significant unmodeled molecular absorbers in the spectral range of the RSS.

Based on the results of this study, comparisons done between direct-beam measurements and calculations for the spectral range 3000-10000 cm^{-1} (3.3-1.0 μm) [Brown et al., 1999; Mlawer et al., 2000], and extensive high-resolution measurement/model comparisons in the longwave (550-3000 cm^{-1} (18.2-3.3 μm)) [Brown et al., 1998; Clough et al., 2000], it can be concluded that state-of-the-art radiative

transfer models accurately account for atmospheric absorption between 550-28500 cm^{-1} (18.2-0.35 μm).

The ability of the method used in this work to detect unmodeled molecular absorption has been probed by repeating the identical procedure described above for the September 18, 1997 case, except with the Chappuis band of ozone (~14000-21000 cm^{-1} (0.71-0.48 μm)) excluded from the LBLRTM and CHARTS calculations. The corresponding results to those of Figures 2a and 2b are shown in Figure 4. The missing absorber in the model is clearly evident in both Figure 4a and in the direct residuals shown in Figure 4b. (Note that, due to the Angstrom fitting procedure described above, the altered direct-beam calculations for this case result in different aerosol optical depths than those used in the original CHARTS calculation.) This result demonstrates that the method used in this work would detect an unmodeled absorption band of similar intensity as the Chappuis band, which absorbs 5.1 W/m^2 of total horizontal irradiance (24.3 W/m^2 of direct-normal irradiance) in this case. Since the absorption by the Chappuis band is far smaller than the claims for missing clear-sky absorption in radiative transfer models, the results presented in this work provide compelling negative evidence contrary to those claims.

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.

The values of single-scattering aldedo used in this work are lower than the aerosol single-scattering albedoes usually assumed in the aerosol community, and, if valid, 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 [e.g. Kiehl et al., 1998] and would represent a substantial source of unmodeled atmospheric absorption.

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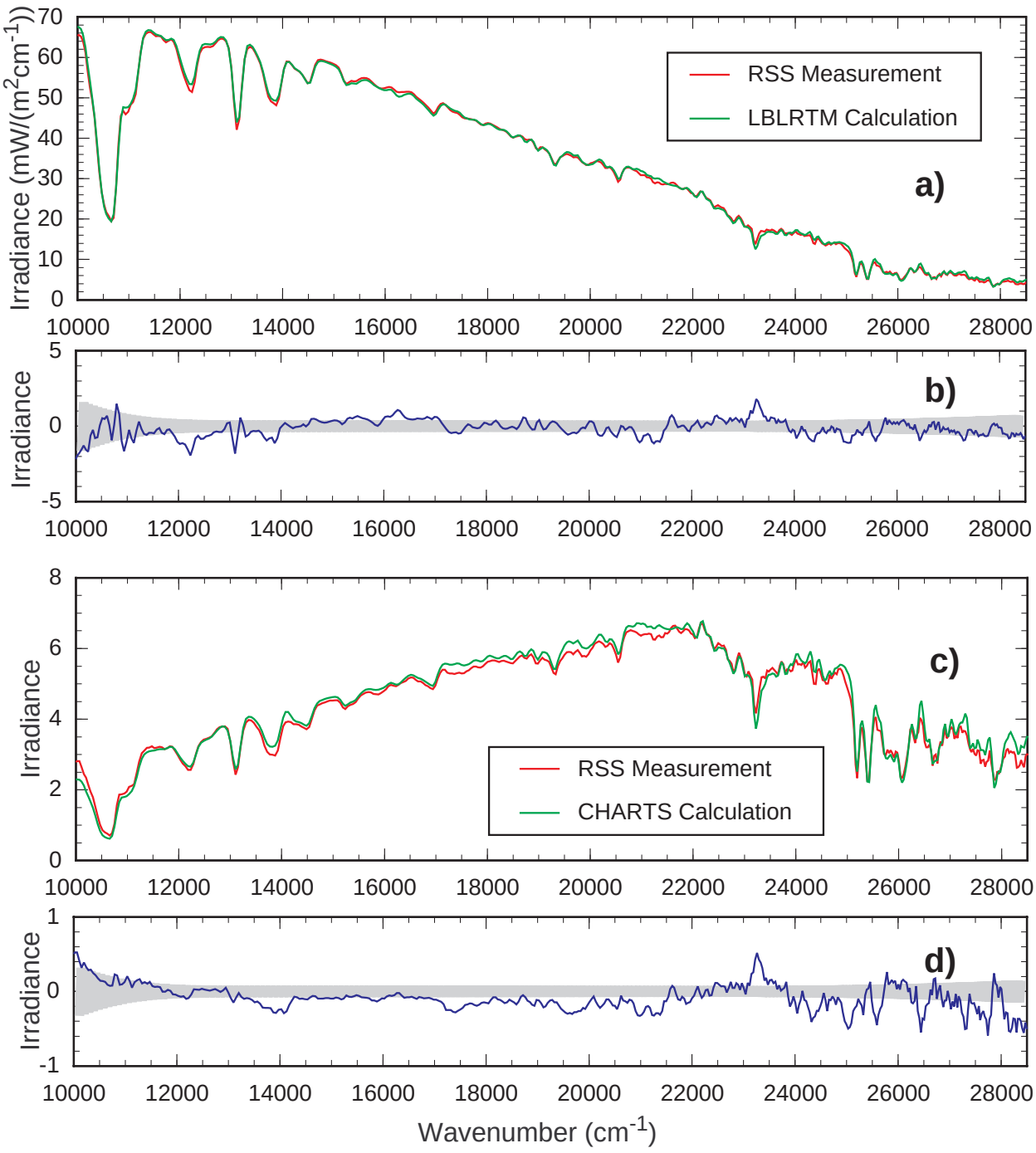

Figure 1. October 2, 1997 case [1.3 airmasses; 2.7 cm vertical PWV]: a) direct-beam spectral irradiances; b) direct-beam differences (RSS-LBLRTM); c) diffuse spectral irradiances; d) diffuse differences (RSS-CHARTS).

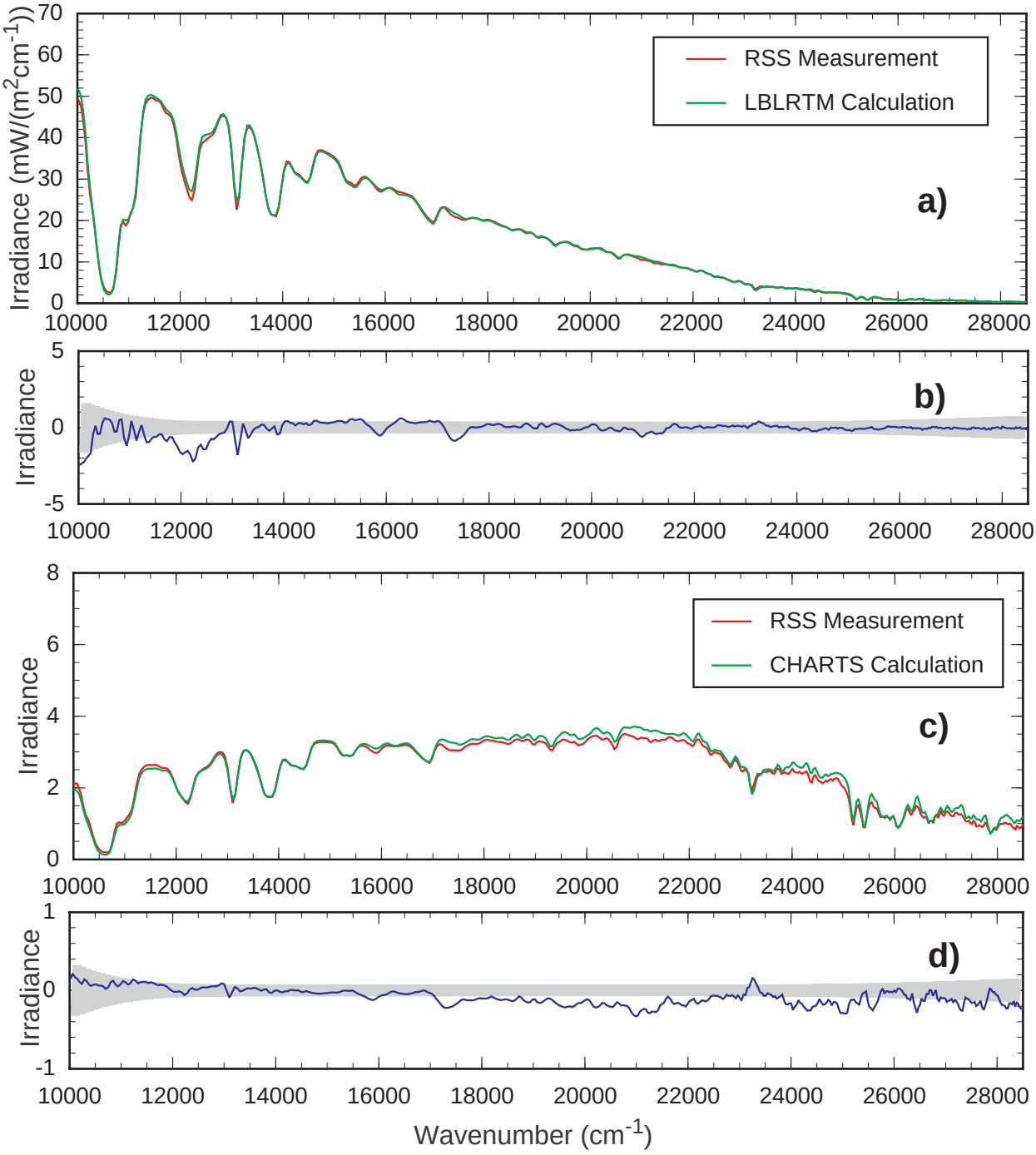

Figure 2. September 18, 1997 case [4.6 airmasses; 4.2 cm vertical PWV]: a) direct-beam spectral irradiances; b) direct-beam differences (RSS-LBLRTM); c) diffuse spectral irradiances; d) diffuse differences (RSS-CHARTS).

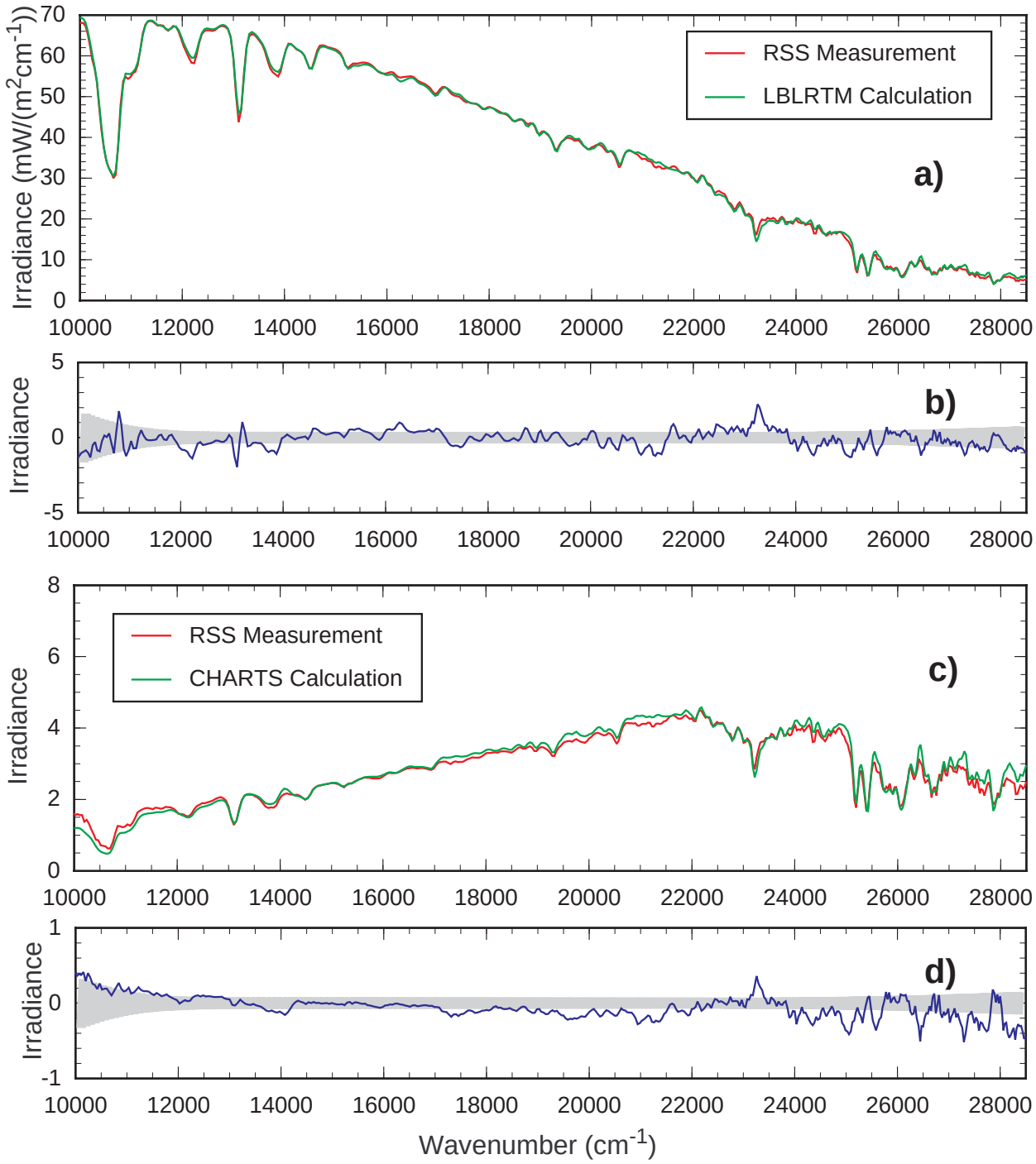

Figure 3. September 29, 1997 case [1.3 airmasses; 1.4 cm vertical PWV]: a) direct-beam spectral irradiances; b) direct-beam differences (RSS-LBLRTM); c) diffuse spectral irradiances; d) diffuse differences (RSS-CHARTS).

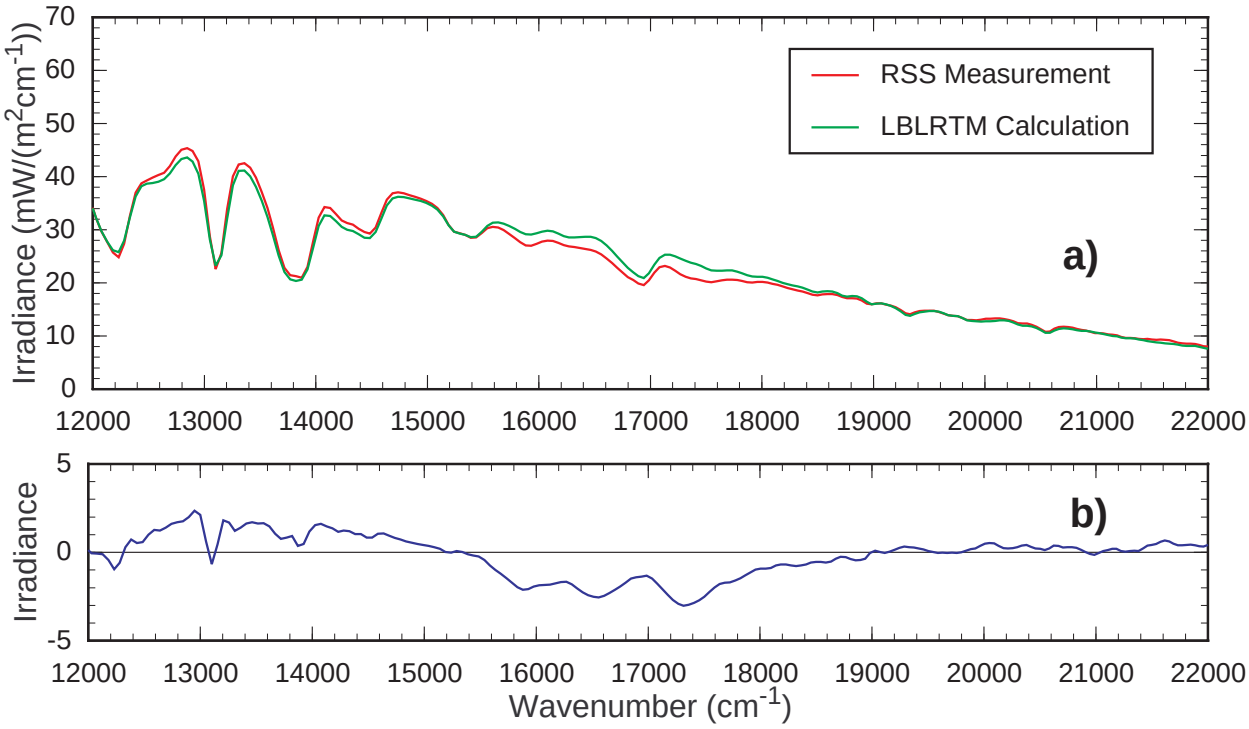

Figure 4. Comparison for October 2, 1997 with Chappuis band of ozone excluded in calculation: a) direct-beam spectral irradiances; b) direct-beam differences (RSS-LBLRTM).