Shortwave Clear-Sky Model-Measurement Intercomparison Using RRTM

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Introduction

The rapid radiative transfer model (RRTM) was developed as part of the Atmospheric Radiation Measurement (ARM) Program. The longwave portion of the model has been extensively validated (Mlawer et al. 1997) and has been successfully incorporated into climate models (Iacono et al. 1998). In the shortwave, direct-beam calculations using RRTM have been compared (Mlawer and Clough 1997; Mlawer and Clough 1998) to those of the line-by-line radiative transfer model (LBLRTM) (Clough and Iacono 1995) and were shown to agree to within 1 W m^{-2}, thereby establishing the accuracy of the k-distributions and other physical quantities used in RRTM to compute the direct beam.

This paper presents the next step in the evaluation of RRTM in the shortwave, the comparison with respect to quality broadband flux measurements of RRTM's direct beam calculations and, additionally, diffuse beam radiative transfer computations done in conjunction with the multiple scattering model discrete ordinate radiative transfer (DISORT) (Stamnes et al. 1988). The use of well-validated gaseous k-distributions in the calculations of diffuse beams fluxes is especially important given the reported discrepancy between modeled and measured diffuse-beam fluxes reported by Kato et al. (1997). This study makes use of the same data set as in Kato et al. (1997), namely clear-sky measurements obtained as part of the ARM Enhanced Shortwave Experiment (ARESE), which was conducted at the ARM Southern Great Plains (SGP) facility in autumn 1995.

Calculations Using Reference Profiles

From validations done using high-resolution measurements by the Absolute Solar Transmittance Interferometer (ASTI), the direct-beam calculations of LBLRTM are known to be highly accurate (Brown et al. 1998; Mlawer et al. 1998). In turn, direct-beam calculations by RRTM for a number of atmospheres have been shown to agree quite well with those of LBLRTM. Table 1 summarizes the results for the surface downward flux (no Rayleigh extinction) for two of the atmospheres examined. The differences at all atmospheric levels are less than 1 W m^{-2}, with good agreement in each spectral band in RRTM. These successful results are due to the accuracy of the optical depths generated by the k-distributions used in RRTM, and, in addition, the approach used in RRTM (both longwave and shortwave) of accounting for the spectral correlation between each band's absorption coefficients and other spectrally dependent physical quantities, such as the solar source function.

Table 1. Comparison of downward direct irradiance, 10-50,000 cm^{-1} (units are Wm^{-2}).

Atmosphere	TOA	RRTM	LBL	DIFF
Mid-latitude summer (MLS), 0°	1366.7	1122.6	1123.5	-0.9
Tropical, 45°	957.1	757.2	757.5	-0.3

Calculations with RRTM have also been performed for four of the cases used in the InterComparison of Radiation Codes used in Climate Models (ICRCCM) study (Fouquart et al. 1991). These cases involve attenuation of the direct beam due to both gaseous absorption and Rayleigh scattering, resulting in the presence of diffuse radiation. In order to perform scattering calculations, the multiple-scattering model DISORT was incorporated into RRTM (the direct-beam results of this combined model are identical to those of RRTM alone). The results of these calculations are summarized in Table 2, which also presents the total downward irradiance calculated by the model of Kato et al. (1997). Because that model and RRTM have been shown to agree closely in their respective calculations of diffuse flux due to Rayleigh scattering (see Table 3), the differences indicated in Table 2, 2 W m^{-2} to 9 W m^{-2}, are likely due to their computations of direct-beam radiation. Because the atmospheric profiles and solar source function used by the two models were not identical, it is unclear to what extent the differences in Table 2 are due to the different approaches used to calculate gaseous absorption.

Calculations Using ARESE Data Set

Motivated by the study presented in Kato et al. (1997), calculations were performed using RRTM for three of the days during the ARESE, which occurred at the ARM SGP site in the autumn of 1995. For these three cloudless days, October 14, 15, and 18, calculations performed every 5 minutes during the afternoon were compared to broadband irradiance measurements taken by radiometers. Because there were a number of instruments taking irradiance measurements as part of the experiment, a judgment was made in Kato et al. (1997) as to the most accurate measured values of direct, diffuse, and total irradiance. [For a more complete discussion of all aspects of this comparison not related to RRTM, including the instrumentation and atmospheric properties used as input to the radiative transfer calculations, see Kato et al. (1997).] These values, which will also be used for this comparison are 1) for direct irradiance, the measurement obtained by the pyrheliometer from the Solar and Infrared Observation System (SIROS) multiplied by 1.021; 2) for the diffuse irradiance, the average of the measurements taken by the SIROS shaded pyranometer and a similar instrument that was part of a "broadband" radiometer system; and 3) for the total irradiance, the sum of the direct and diffuse values.

The input to the RRTM calculations was the same as in Kato et al. (1997). The pressure, temperature, and water vapor profiles were obtained from radiosonde soundings taken every 3 hours and interpolated to 5-minute intervals. For ozone, below 35 km an average of 32 ozone soundings taken during ARESE were used, with the MLS ozone profile used above 35 km. The surface albedos used for the calculations were 1-minute averages (done at 5-minute intervals) of the ratio of upwelling and downwelling shortwave surface irradiances measured by pyranometers. For the calculations involving aerosol, a mineral aerosol was assumed, with the optical thickness determined from an Angstrom relation based on 1-hour averages of measurements taken by the Pennsylvania State University (PSU) sun photometer at six frequencies. The other aerosol scattering properties, the single scattering albedo and the asymmetry parameter, were obtained from Mie calculations at 545 nm using the size distribution inferred from the

Table 2. Calculation of surface downward irradiance for four ICRCCM cases (surface albedo = 0.2, units are Wm^{-2}).

	RRTM			Kato et al. (1997)	
Atmosphere	**Direct**	**Diffuse**	**Total**	**Total**	**Diff**
MLS, 30°	858	64	922	925	-3
MLS, 75°	188	37	225	227	-2
Tropical, 30°	839	63	903	912	-9
Tropical, 45°	182	37	218	224	-6

Table 3. Model calculations for three ARESE days with no aerosol (units are Wm^{-2}).

	RRTM			Kato et al. (1997)		
Date	**Direct**	**Diffuse**	**Total**	**Direct**	**Diffuse**	**Total**
October 14	680	58	737	686	57	743
October 15	668	57	726	675	57	732
October 18	639	57	696	647	56	703
Average	662	57	720	669	57	726

aerosol optical thickness measured in the afternoon. The solar source function used in RRTM is from Kurucz (1992), with the solar zenith angle and earth-sun distance calculated every 5 minutes.

Using these properties as input to RRTM (with DISORT), initial calculations were performed with no aerosols, i.e. only Rayleigh scattering. Presented in Table 3 are the results of these calculations and the corresponding results of Kato et al. (1997), both performed at 5-minute intervals from 1 p.m. to 5 p.m. local time (1600 UT to 2000 UT) on each of the 3 days and then averaged. (The vertical water vapor column amounts for the 3 days were 1.0 cm, 1.2 cm, and 1.8 cm, respectively.) The two models agree quite closely in their calculations of the diffuse radiation resulting from Rayleigh scattering. This is in contrast to the direct-beam calculations, which differ by an average of 7 W m^{-2}, consistent with the results in Table 2. It is worth noting that the magnitude of this difference is modest compared to the differences between direct-beam calculations in the ICRCCM study (Fouquart et al. 1991). Also important to emphasize is, given the results in Table 1, the direct-beam calculations of RRTM for these ARESE cases should be considered effectively equivalent to the values that would have been obtained using the line-by-line model LBLRTM.

For October 14, the irradiances calculated by RRTM (with DISORT, 8-streams) with the inclusion of a mineral aerosol are shown in Table 4. Also shown are the corresponding calculations of Kato et al. (1997) and the irradiance measurements of the instruments discussed above. All results in this table are averages of irradiances obtained every 5 minutes from 1 p.m. to 5 p.m. local time. The difference between the average of the direct-beam calculations of RRTM and the Kato et al. model, 8 W m^{-2}, is consistent with the direct-beam differences in Tables 2 and 3, with RRTM again showing somewhat more gaseous absorption. The average measured direct beam irradiance is 6 W m^{-2} higher than the calculation of RRTM, most likely due to inaccurate specification of the atmospheric state or measurement error by the radiometer. The average diffuse beam irradiance computed by RRTM (a single-scattering albedo of 0.90 was used with an asymmetry parameter of 0.69 and a Henyey-Greenstein phase function) is very consistent with that of Kato et al. (1997) and is higher than the measured average irradiance by 31 W m^{-2}. As was pointed out in Kato et al. (1997), any computation of the diffuse irradiance will necessarily be higher than the measured value since Rayleigh scattering provides enough diffuse radiation by itself to provide agreement with the measurement on this day. However, the shaded pyranometer has recently been estimated to have a possible low bias of ~10 W m^{-2} (L. Harrison, private communication), which would imply that the diffuse irradiance due to aerosol on October 14 is of this order. This would result in a model-measurement discrepancy of ~21 W m^{-2}.

Any attempt to eliminate this discrepancy by lowering the aerosol-generated diffuse irradiance calculated by the model must most likely involve the entire shortwave region since about 30% of this irradiance (9 W m^{-2}) is in the infrared region, with the rest in the visible. One possible source of error in the calculation is the use of aerosol extinction coefficients obtained from the Angstrom relationship derived in Kato et al. (1997) from the PSU sun photometer measurements. Instead, if the aerosol extinction coefficients are inferred from the multifilter rotating shadowband radiometer (MFRSR) (Harrison et al. 1994) measurements, using the smallest possible values that this data will support, the discrepancy is lowered by 10 W m^{-2}, to ~11 W m^{-2}. In addition, a sensitivity test shows that the diffuse irradiance will be lowered by a further 5 W m^{-2} if the single-scattering albedo of the aerosol were 0.75 instead of the assumed 0.90. This is a reasonable value to use for this scattering parameter in this sensitivity analysis, given the uncertain knowledge of the aerosol properties at the measurement location. With these changes, the model-measurement discrepancy is much less problematic.

Summary

The study presented here indicates that there is a sizable discrepancy between the diffuse irradiance measured on October 14, 1995, as part of the ARESE experiment and the corresponding calculations of RRTM, thereby supporting the results presented in Kato et al. (1997). However, reasonable changes to the scattering properties of the assumed aerosol reduce this discrepancy to the magnitude of possible experimental error. Therefore, a likely explanation for the reported discrepancy between the diffuse beam measurements and radiative transfer calculations is a

Table 4. Comparison for October 14 of measurement and model with mineral aerosol (units are Wm^{-2}).

	RRTM	Kato et al.	Best Measurement	Broadband	SIROS
Direct	640	648	646	647	633
Diffuse	88	86	57	59	54
Total	728	734	703	706	687

combination of inaccurate specification of the aerosol scattering properties and measurement error by the instruments employed. More investigation of the error in the diffuse irradiance measurement is needed before this statement can be made definitively.

In addition, RRTM (with DISORT) has been shown to be a good tool for computing both the direct and diffuse irradiance, which is to a large extent a result of the well-validated nature of its gaseous absorption coefficients.

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