Validation of the RRTM Shortwave Radiation Model and Comparison to GCM Shortwave Models

M. J. Iacono, E. J. Mlawer, and S. A. Clough
Atmospheric and Environmental Research, Inc.
Lexington, Massachusetts

Introduction

An important step toward improving radiative transfer codes in general circulation models (GCMs) is to thoroughly evaluate them either by comparison to measurements directly or by comparing them to other data-validated radiation models. The Rapid Radiative Transfer Model (RRTM) shortwave (SW) radiation model accurately reproduces direct beam fluxes from the Line-by-Line Radiative Transfer Model (LBLRTM) (Clough and Iacono 1995), and direct and diffuse fluxes from Code for High-resolution Accelerated Radiative Transfer with Scattering (CHARTS); (Moncet and Clough 1997). All three models were developed at Atmospheric and Environmental Research, Inc. with support from the Atmospheric Radiation Measurement (ARM) Program. Shortwave clear-sky fluxes from two operational GCMs are evaluated by comparison to RRTM_SW for several standard profiles.

RRTM is an accurate and efficient, correlated-k, longwave (LW) and SW radiative transfer model (Mlawer et al. 1997) that has been developed to address the ARM objective of improving radiation models in GCMs. RRTM LW has been shown to have a beneficial impact on the National Center for Atmospheric Research (NCAR) Community Climate Model, CCM3 (Iacono et al. 2000), and is in operational use at European Center for Medium-Range Weather Forecasts (ECMWF) in their weather forecast model (Morcrette et al. 2001). The absorption coefficients required for RRTM are derived from LBLRTM, thus providing a link between ARM measurements and a radiation model that is sufficiently fast for GCM applications. This project establishes that application of RRTM SW can provide additional improvement to GCMs.

LBLRTM/CHARTS SW Validations

High-resolution irradiance validations of LBLRTM and CHARTS using Rotating Shadowband Spectroradiometer (RSS) ARM measurements have been performed for several clear-sky cases at three precipitable water amounts (Mlawer et al. 2000). These showed LBLRTM direct beam differences on the order of 1 $mWm^{-2}(cm^{-1})^{-1}$ and integrated residuals of 2-3 Wm^{-2} when compared to observations. Diffuse spectral irradiance validations between CHARTS and RSS also showed excellent agreement, with differences of less than 1 $mWm^{-2}(cm^{-1})^{-1}$ and integrated residuals of less than 0.2 Wm^{-2}. The calculations above used an aerosol optical depth determined by fitting an Angstrom relation based on the ratio of the direct beam measurements to a direct beam calculation without aerosols.

RRTM/CHARTS Shortwave Comparison

A band-by-band comparison of downward SW surface fluxes between RRTM and CHARTS is shown in Table 1 for both direct and diffuse solar calculations for a standard tropical atmosphere with the sun at zenith. Good agreement between the models to less than 1 Wm^{-2} is noted in each spectral band. RRTM calculations used the discrete ordinates model, DISORT, for radiative transfer using four streams. The total (direct plus diffuse) flux difference, integrated over the RRTM bands, indicates that RRTM SW and CHARTS agree to within 1.5 Wm^{-2}. The magnitude of the integrated difference is close to 1 percent for the diffuse beam and less than 0.1 percent for the direct flux.

Table 1. Comparison for the RRTM bands of downward SW direct and diffuse surface fluxes calculated by RRTM and CHARTS for the standard tropical atmosphere with the sun at zenith.

Wavenumber Range (cm^{-1})	DIRECT SW Flux (W/m^2)			DIFFUSE SW Flux (W/m^2)		
	RRTM	CHARTS	RRTM-CHARTS	RRTM	CHARTS	RRTM-CHARTS
2600-3250	5.75	5.27	0.48	0.00	0.00	0.00
3250-4000	0.12	0.24	-0.12	0.00	0.00	0.00
4000-4650	16.94	16.83	0.11	0.00	0.00	0.00
4650-5150	13.83	13.52	0.31	0.00	0.00	0.00
5150-6150	27.68	28.55	-0.87	0.02	0.02	0.00
6150-7700	44.34	44.33	0.01	0.05	0.04	0.01
7700-8050	22.51	22.43	0.07	0.05	0.05	0.00
8050-12850	267.50	267.32	0.18	2.01	2.00	0.01
12850-16000	194.40	193.88	0.52	4.96	4.94	0.02
16000-22650	300.51	300.48	0.03	26.52	25.98	0.55
22650-29000	88.53	88.59	-0.06	25.57	25.46	0.11
29000-38000	12.98	12.88	0.10	9.73	9.65	0.08
38000-50000	0.00	0.00	0.00	0.00	0.00	0.00
2600-50000	995.09	994.32	0.76	68.91	68.14	0.78

RRTM Shortwave Radiative Transfer

In RRTM_SW, radiative transfer can be calculated with the discrete-ordinates model (DISORT), or with a faster, though less accurate 2-stream method derived from the collaborative 3ARM radiation model. Figure 1 shows fluxes and heating rates calculated by RRTM using DISORT with 16 streams (left panels). The flux and heating rate differences between DISORT and the 2-stream method are shown in the right panels of Figure 1. These results are for clear-sky with Rayleigh scattering only for a mid-latitude summer atmosphere and a solar zenith angle of 30 degrees. Two-stream fluxes are within 1 Wm^{-2} of DISORT at all levels, and heating rate is within 0.1 Kd^{-1}. The two-stream approach provides significantly faster performance while retaining most of the accuracy of DISORT and will be utilized to prepare a version of RRTM_SW that can be implemented and tested within GCMs.

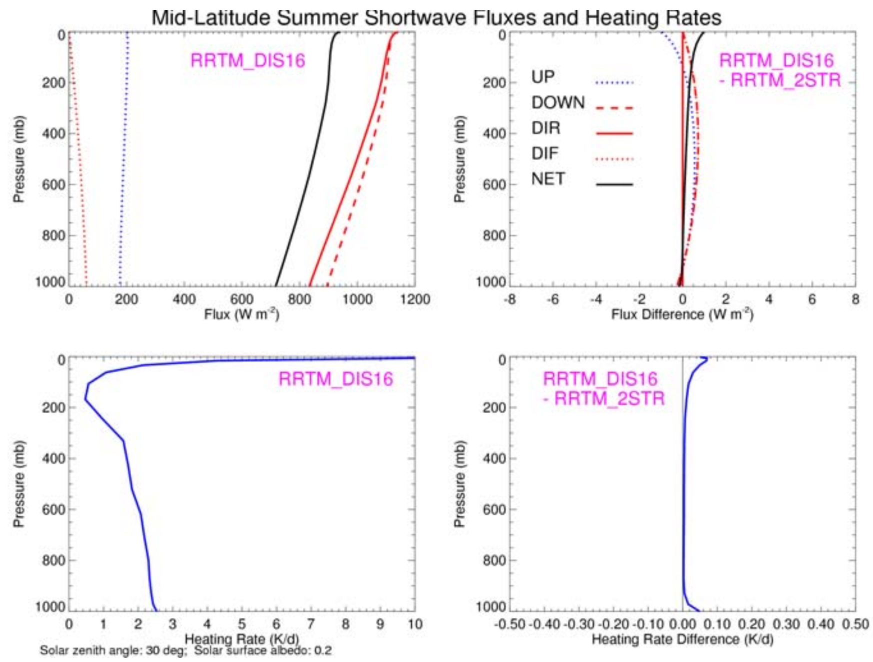

Figure 1. Mid-latitude summer, clear-sky SW up, down, and net fluxes and heating rate for RRTM using DISORT with 16 streams (left) and the difference between the 16-stream and the 2-stream radiative transfer results with RRTM (right) for a 30 degree solar zenith angle and a surface albedo of 0.2.

Comparisons to GCM Shortwave Models

Having established the accuracy of RRTM_SW through its link to ARM measurements, we have compared single-column calculations with this model (using the 2-stream radiative transfer method) to SW calculations from CCM3 and the ECMWF weather forecast model for several standard, clear-sky atmospheric profiles. These calculations indicate that these GCMs substantially overestimate the clear-sky downward SW surface flux relative to RRTM.

Clear-sky SW fluxes and heating rates calculated with the CCM3 SW model are shown in Figure 2 (left panels) for a mid-latitude summer (MLS) atmosphere, a 30-degree solar zenith angle, and a surface albedo of 0.2. Differences between RRTM and the CCM3 SW model are also shown in Figure 2 (right panels). Relative to RRTM, CCM3 calculates an excess of downward SW flux to the surface of 13 Wm^{-2} for this case. This excess is somewhat less for a greater (75 degree) solar zenith angle as shown in Figure 3. Table 2 summarizes the downward SW surface fluxes for each model for tropical (TRP), mid-latitude summer, and sub-arctic winter (SAW) atmospheres at either 30 or 75 degree solar zenith angles. Fluxes are indicated for the direct and diffuse components and the total flux. Also shown in Table 2, are the MLS fluxes with standard CCM3 aerosols included in the calculation. Note that the direct flux differences are larger than for the total flux, since they are partly compensated by diffuse flux differences of opposite sign.

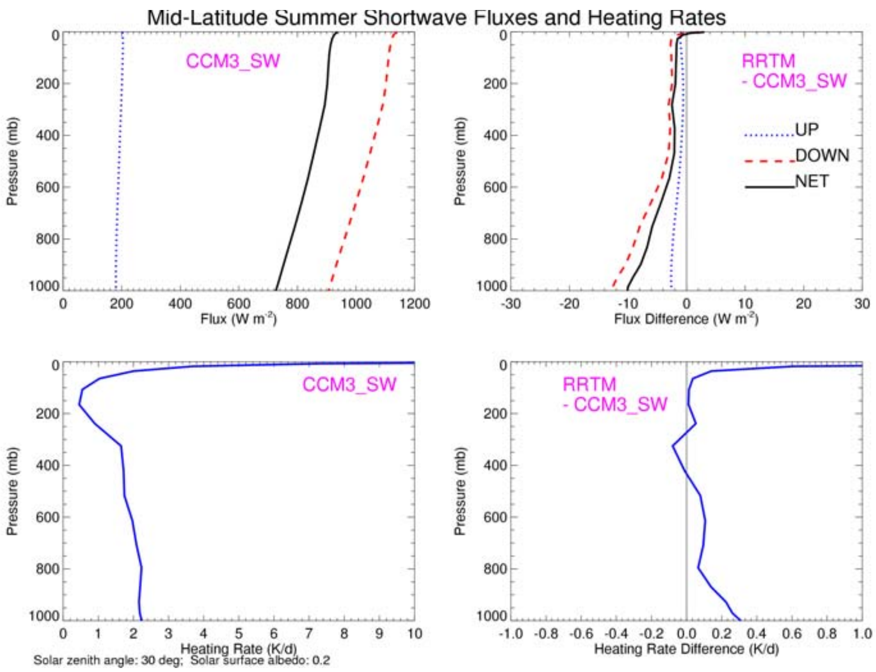

Figure 2. Mid-latitude summer, clear sky SW up, down, and net fluxes and heating rates for the CCM3 SW model (left) and the difference between the RRTM and CCM3 SW calculations (right) for a 30 degree solar zenith angle and a surface albedo of 0.2.

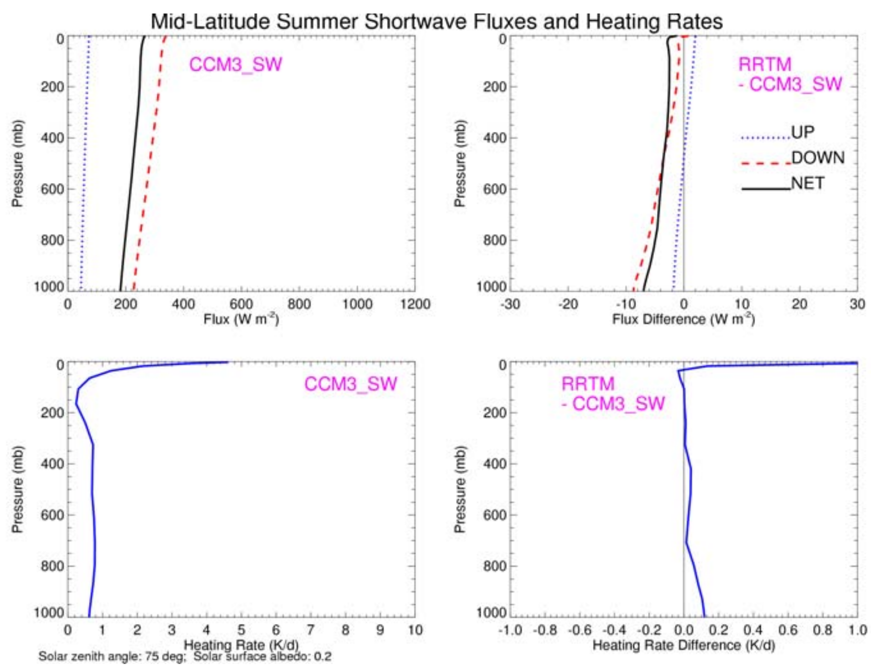

Figure 3. Mid-latitude summer, clear sky SW up, down, and net fluxes and heating rates for the CCM3 SW model (left) and the difference between the RRTM and CCM3 SW calculations (right) for a 75 degree solar zenith angle and a surface albedo of 0.2.

Table 2. Clear-sky direct, diffuse, and total downward SW surface fluxes for RRTM_SW and CCM3_SW for tropical, mid-latitude summer, and sub-arctic winter profiles at 30 and 75 degree solar zenith angles with and without standard CCM3 aerosols.

	RRTM_SW (W m^{-2})			CCM3_SW (W m^{-2})			RRTM - CCM3 (W m^{-2})		
Atmosphere	**Direct**	**Diffuse**	**Total**	**Direct**	**Diffuse**	**Total**	**Direct**	**Diffuse**	**Total**
Without Aerosols									
TRP 30	814	62	876	838	54	892	-24	8	-16
MLS 30	830	62	891	851	53	904	-21	9	-13
MLS 75	181	36	218	190	36	226	-9	0	-8
SAW 75	221	39	260	226	38	264	-5	1	-4
With Aerosols									
MLS 30	670	207	877	702	185	887	-32	22	-10
MLS 75	100	96	196	110	93	204	-10	3	-8

Clear-sky fluxes and heating rates calculated with the SW code from the operational ECMWF weather forecast model are shown in Figure 4 for the MLS atmosphere at a 30-degree solar zenith angle (left panels). Differences between RRTM and ECMWF (right panels) show that the ECMWF model calculates an excess of 30 Wm^{-2} in downward SW flux to the surface. At a 75 degree solar zenith angle in this atmosphere, the excess downward surface flux calculated by ECMWF relative to RRTM is about 10 Wm^{-2}. These results use the currently operational four-band version of the ECMWF SW model, which is being updated to a six-band version that is expected to address these discrepancies.

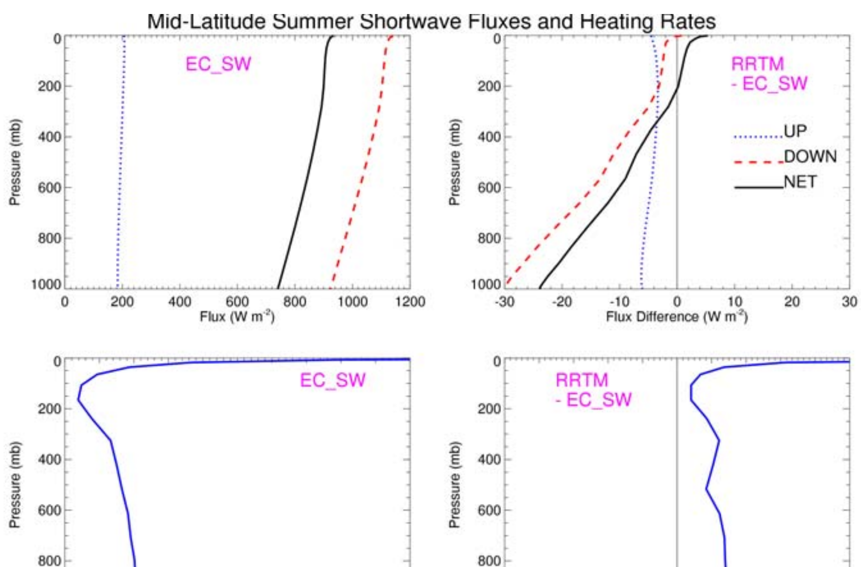

Figure 4. Mid-latitude summer, clear-sky SW up, down, and net fluxes and heating rates for the operational four-band ECMWF SW model (left) and the difference between the RRTM and ECMWF SW calculations (right) for a 30 degree solar zenith angle and a surface albedo of 0.2.

Summary

Shortwave RSS radiation measurements from the ARM Program have been used to demonstrate that LBLRTM direct beam calculations and CHARTS diffuse calculations are able to reproduce observed spectral radiance with high accuracy. These models are, in turn, used to establish that RRTM SW, using a DISORT 4-stream calculation for radiative transfer, retains an accuracy of less than 1.5 Wm^{-2} in each band and for the total SW spectrum. Use of a faster two-stream radiative transfer method in RRTM produces a clear sky accuracy of 2 Wm^{-2} for Rayleigh scattering only and 2-3 Wm^{-2} when CCM3 aerosols are included. When compared to two GCM SW models (CCM3 and ECMWF), RRTM demonstrates that the CCM3 climate model and the ECMWF forecast model significantly overestimate downward SW surface fluxes by as much as 10-15 Wm^{-2} and 20-30 Wm^{-2}, respectively. This illustrates the critical need to improve and validate clear sky SW absorption in GCMs before more complex processes, such as cloud radiative effects, are considered to explain significant discrepancies between modeled and observed SW fluxes.

Acknowledgment

The authors thank Jean-Jacques Morcrette of ECMWF for providing the ECMWF SW model for this project.

References

Clough, S. A., and M. J. Iacono, 1995: Line-by-line calculation of atmospheric fluxes and cooling rates, 2, Application to carbon dioxide, ozone, methane, nitrous oxide, and the halocarbons. *J. Geophys. Res*., **100**, 16,519-16,535.

Iacono, M. J., E. J. Mlawer, S. A. Clough, and J.-J. Morcrette, 2000: Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3. *J. Geophys. Res*., **105**, 14,873-14,890.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res*., **102**, 16,663-16,682.

Mlawer, E. J., et al., 2000: Comparison of spectral direct and diffuse solar irradiance measurements and calculations for cloud-free conditions. *Geophys. Res. Lett*., **27**, 2653-2656.

Moncet, J. L., and S. A. Clough, 1997: Accelerated monochromatic radiative transfer for scattering atmospheres: Application of a new model to spectral radiance observations. *J. Geophys. Res*., **102**, 21,853-21,866.

Morcrette, J.-J., E. J. Mlawer, M. J. Iacono, and S. A. Clough, 2001: Impact of the radiation-transfer scheme RRTM in the ECMWF forecast system. Technical report in the ECMWF Newsletter, No. 91.