Cloudy Sky RRTM Shortwave Radiative Transfer and Comparison to the Revised ECMWF Shortwave Model

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Introduction

An important step toward improving radiative transfer codes in general circulation models (GCMs) is their thorough evaluation by comparison to measurements directly, or to other data-validated radiation models. This work extends the clear-sky shortwave (SW) GCM evaluation presented by Iacono et al. (2001) to computations including clouds. The rapid radiative transfer model (RRTM) SW radiation model accurately reproduces clear-sky 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. (AER) with support from the Atmospheric Radiation Measurement (ARM) Program and have been carefully evaluated with ARM measurements.

RRTM is an accurate and efficient, correlated-k longwave (LW) and SW radiative transfer model (Mlawer et al. 1997) that addresses the ARM objective of improving radiation models in GCMs. The absorption coefficients required for RRTM are derived from LBLRTM, thus providing a link between ARM measurements and a radiation model that can be applied to GCM evaluation. 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 it is in operational use in the European Centre for Medium-Range Weather Forecasts (ECMWF) weather forecast model (Morcrette et al. 2001). In prior work, two GCM SW models (NCAR CCM3 and ECMWF) were shown to be in substantial disagreement with RRTM in clear-sky, producing downward SW surface flux differences of 10-30 Wm^{-2} and heating rate differences as high as 0.4 K d^{-1} (Iacono et al. 2001).

The ECMWF SW model has been updated recently from four spectral bands to a six-band version, and the current work reevaluates this model in clear-sky using RRTM. Changes include dividing the former 0.25-0.69 micron interval into two separate bands and adding a band in the ultraviolet from 0.185 to 0.25 microns. In addition, the SW RRTM has been modified to include absorption from both liquid and ice clouds. RRTM fluxes are calculated (using a 16-stream DISORT calculation for radiative transfer) for a tropical profile including an overcast liquid cloud and are compared to CHARTS. The revised six-band ECMWF SW model is then reevaluated using RRTM for the same low cloud case.

RRTM/CHARTS SW Cloud Comparison

Shortwave fluxes calculated by CHARTS and RRTM and the modeled flux differences are shown in Table 1 for the low cloud tropical atmosphere of Barker et al. (2002). The overcast liquid cloud consists of spherical droplets, is located in the layer from 3.5 to 4 km, has a mixing ratio of 0.159 g/kg, and has a visible optical depth close to 10. Both models use the liquid cloud parameterization of Hu and Stamnes (1993). Downwelling fluxes are shown for the top of the atmosphere, cloud top, cloud bottom, and the surface for both the direct and diffuse components at a solar zenith angle (SZA) of 60 degrees. Upwelling diffuse SW fluxes are also shown at the same levels. All fluxes are integrated over the 2600-50000 cm^{-1} spectral region. In general, RRTM fluxes are within 0.6 W m^{-2} of the fluxes calculated by CHARTS. The upwelling diffuse flux from the top of the cloud is 1.1 W m^{-2} lower in RRTM.

Table 1. Comparison of SW direct and diffuse fluxes calculated by RRTM and CHARTS in the standard tropical profile for an opaque liquid cloud from 3.5 to 4 km and a SZA of 60 degrees.

RRTM/CHARTS Shortwave Flux Comparison (Low Cloud)						
	Diffuse SW Flux (W m^{-2})			Direct SW Flux (W m^{-2})		
Direction/ Level	**RRTM**	**CHARTS**	**RRTM-CHARTS**	**RRTM**	**CHARTS**	**RRTM-CHARTS**
Down/ TOA	0.0	0.0	0.0	684.67	684.64	+0.03
Down/ CloudTop	50.92	50.53	+0.38	527.10	526.85	+0.25
Down/ CloudBot	247.18	247.79	-0.61	0.0	0.0	0.0
Down/ Surface	223.09	223.49	-0.40	0.0	0.0	0.0
Up/ TOA	353.03	353.41	-0.38	_	_	_
Up/ CloudTop	352.59	353.71	-1.12	_	_	_
Up/ CloudBot	48.68	48.67	+0.01	_	_	_
Up/ Surface	44.62	44.70	-0.08	_	_	_

ECMWF SW Clear-Sky Evaluation

Clear-sky SW fluxes calculated with the 4-band ECMWF SW model (SW4), the updated 6-band model (SW6) and the differences from RRTM are shown in the top panels of Figure 1 for a tropical atmosphere with the sun at zenith and a surface albedo of 0.2. For this case, SW6 reduced the downward surface flux difference from 36 W m^{-2} to 10 W m^{-2} with a similar reduction in the net flux. Downward and net fluxes were improved with SW6 throughout the lower and middle troposphere though they become somewhat too high in the upper troposphere. Heating rates for all three models and the differences between RRTM and the two ECMWF SW models are shown on a logarithmic scale in the center panels of Figure 1 to highlight the stratosphere and on a linear scale in the lower panels to emphasize the troposphere. Heating rate is generally improved by SW6, particularly in the stratosphere above 10 mb and in the lower troposphere, though differences of 0.2 K d^{-1} still occur.

Clear-sky downward surface fluxes calculated with RRTM and the two ECMWF models for several standard atmospheres and solar zenith angles are listed in Table 2. Fluxes are improved in all cases, with the largest improvement occurring in the wetter atmospheres and lower SZA. In some cases at low SZA, the excess downward surface flux from SW4 has become a small deficit in SW6.

ECMWF SW Cloudy Sky Evaluation

Having established in Table 1 the accuracy of RRTM relative to the high-resolution multiple scattering model CHARTS for a cloud case, RRTM is then used to evaluate calculations from the ECMWF SW models for the same cloud case with the sun at zenith. The ECMWF models use the liquid cloud parameterization of Slingo (1989). Upward, downward, and net fluxes calculated with SW4 and SW6 and their differences from RRTM are plotted in the upper panels of Figure 2 for the liquid cloud case described earlier. Downward fluxes below the cloud from SW4 are roughly 10 W m^{-2} too low relative to RRTM, and this deficit is increased to 20 W m^{-2} with SW6. Upward fluxes below the cloud from the ECMWF models are generally a few W m^{-2} too low compared to RRTM. Above the cloud, SW6 improves both the upward and downward fluxes by about 5 W m^{-2}, though large differences remain, especially directly above the cloud top. The heating rates and differences are shown in the lower panels of Figure 2. Improvement is seen at most levels as a result of SW6, except just below the cloud base near 700 mb.

Summary

Prior work showed that RRTM total SW fluxes agree with the data-validated high-resolution model CHARTS to within 1.5 W m^{-2} for clear-sky calculations. A parameterization for liquid clouds has been implemented in RRTM SW and calculations with a single-layer, optically thick, overcast liquid cloud show agreement with CHARTS to within 1.2 W m^{-2} for both direct and diffuse flux. Previous comparisons between RRTM and two widely used GCM SW models showed considerable clear-sky discrepancies. This illustrated 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. Recent revisions to the ECMWF SW model have significantly improved its clear sky fluxes and heating rates relative to RRTM over the previous 4-band ECMWF SW model. Calculations with a liquid cloud also suggest some improvement though this may be partly impacted by the different parameterizations for liquid cloud absorption applied in the ECMWF and RRTM SW models.

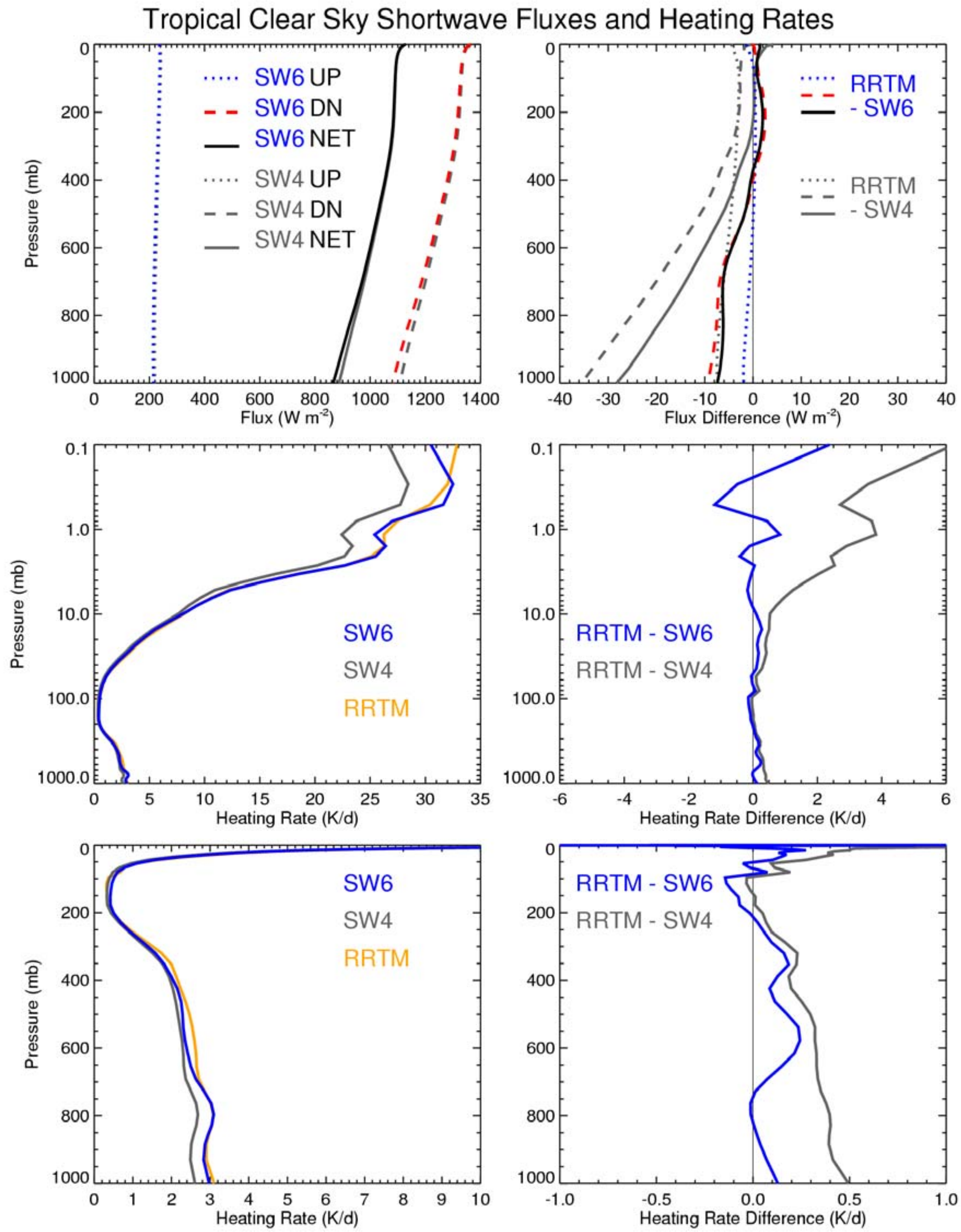

Figure 1. Tropical, clear-sky SW calculations with the 4-band ECMWF SW model (SW4), the updated 6-band ECMWF model (SW6) and the differences from RRTM of upward, downward and net flux (top panels) in units of W m^{-2}. SW heating rates for the three models and the RRTM-ECMWF differences are shown on a logarithmic scale (center panels) and a linear scale (bottom panels) in units of K d^{-1}.

Table 2. Clear-sky downward SW surface fluxes for RRTM, the ECMWF 4-band SW model (SW4) and the updated 6-band model (SW6) for tropical, mid-latitude summer, and sub-arctic winter profiles at several SZA with aerosols excluded. Units are W m^{-2}.

RRTM and ECMWF Clear-Sky Downward Surface Fluxes				
Atmosphere	**RRTM_SW**	**ECMWF_SW6**	**RRTM – SW6**	**RRTM – SW4**
Tropical SZA = 0	1067.6	1077.0	-9.4	-36.1
Tropical SZA = 30	908.9	916.6	-7.7	-32.4
Tropical SZA = 75	221.7	220.3	+1.4	-11.0
Mid-lat summer SZA = 30	921.3	929.9	-8.6	-31.4
Mid-lat summer SZA = 75	223.1	224.5	-1.4	-12.6
Sub-arc winter SZA = 75	252.2	250.5	+1.7	-6.0

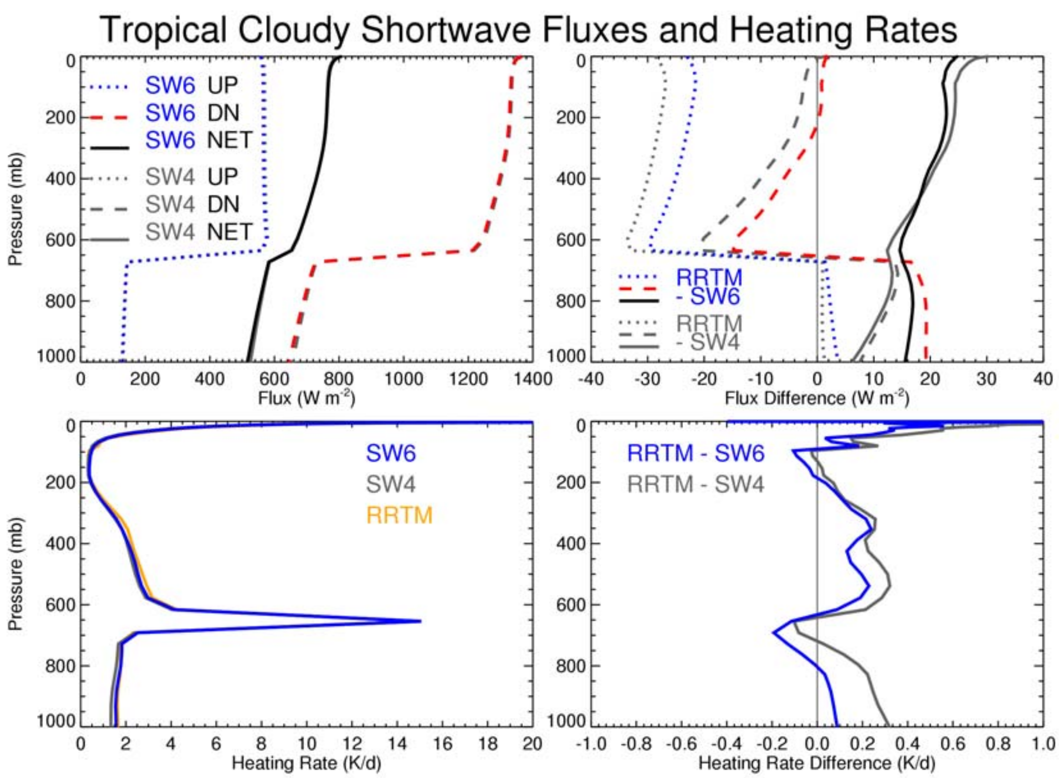

Figure 2. Tropical, cloudy sky SW calculations with the 4-band ECMWF SW model (SW4), the updated 6-band ECMWF model (SW6) and the differences from RRTM of upward, downward and net flux (top panels) in units of W m^{-2} for an overcast liquid cloud and a SZA of 0. SW heating rates for the three models and the RRTM-ECMWF differences (bottom panels) are in units of K d^{-1}.

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