Shortwave and Longwave Enhancements in the Rapid Radiative Transfer Model

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Introduction

This work describes recent advances in the rapid radiative transfer model (RRTM) (Mlawer et al. 1997), a rapid and accurate model designed for climate applications. The initial phase of RRTM, which uses the correlated-k method for radiative transfer, allowed the calculation of fluxes and cooling rates in the longwave region in clear-sky conditions. These calculations have been shown to be accurate relative to fluxes and cooling rates calculated by the well-validated line-by-line radiative transfer model (LBLRTM) (Clough et al. 1992; Clough and Iacono 1995), providing a traceable link from RRTM to observations done at the highest spectral resolution.

The longwave method in RRTM has been extended to include the contributions of cloud absorption and emission. Various parameterizations have been implemented for both liquid and ice clouds, which are allowed to be independently specified when running the model. In addition, the clear-sky longwave approach in RRTM has been extended to the shortwave region, allowing direct solar fluxes and cooling rates to be computed for the spectral range 2,600-50,000 cm^{-1}. The results of these calculations by RRTM have been compared with calculations by LBLRTM and show substantial agreement. Presented in this work are various shortwave results of RRTM, including a calculation of the solar flux absorbed by the water vapor continuum.

Longwave Cloud Method

There are multiple options available in RRTM for the determination of the optical depths of cloudy atmospheric layers. All options require the specification of the cloud fraction f_{cld} for each layer. The default option allows the user to directly input the optical depth (treated as gray) due to the clouds in each layer. There is one other option available that combines the effects of liquid and ice clouds. This is the cloud parameterization in the National Center for Atmospheric Research's community climate model CCM2 (Hack et al. 1993), which treats the cloud optical depth (treated as gray) as proportional to the cloud liquid water, with a constant of proportionality of 0.06024 m^2/g.

All other methods available for the calculation of the optical depths of cloudy layers involve separate computations of the effects of liquid and ice clouds and, therefore, require the specification of the ice fraction for each cloudy layer. The optical depth is then given by

$$\tau_{cld} = CWP\left[\left(1-f_{ice}\right)k_{liq} + f_{ice}k_{ice}\right] \tag{1}$$

where CWP is the cloud water path for the layer and k_{liq} and k_{ice} are the liquid cloud and ice cloud absorption coefficients, respectively. There are two liquid cloud parameterizations available, one gray and the other with spectral definition. In the gray parameterization, which is from CCM3 (Kiehl et al. 1996) k_{liq} is a constant, 0.09036 m^2/g. The other liquid cloud method is due to Hu and Stamnes (1993) and is based on Mie calculations assuming spherical droplets. In this approach, the extinction coefficient can be expressed in terms of parameters A_v, B_v and C_v as

$$e_{liq}(v) = A_v\left(r_{liq}\right)^{B_v} + C_v \tag{2}$$

where r_{liq} is the effective radius of the liquid droplets (in microns). This equation and a similar one for the single-scattering albedo allow the calculation of values of k_{liq}, which are stored for a range of values of r_{liq} for each spectral band in RRTM. In addition to the two liquid cloud parameterizations, there are three ice cloud methods implemented in RRTM. The simplest is from CCM3 and treats ice as a gray absorber with absorption coefficient (in m^2/g) given by

$$k_{ice} = 0.005 + \frac{1}{r_{ice}} \tag{3}$$

where r_{liq} is the effective ice radius (in microns). This method is a simplification of the parameterization due to Ebert and Curry (1992), which is based on Mie calculations using spheres with equivalent surface area as particles in a size distribution of hexagonal ice crystals. This parameterization also forms the basis for the second ice cloud method available in RRTM. The coefficients in Ebert and Curry (1992), which are spectrally dependent, are translated as closely as possible to the spectral bands in RRTM, allowing the calculation of the ice absorption coefficient in terms of parameters A_j and B_j as

$$k_{ice} = A_j + \frac{B_j}{r_{ice}} \tag{4}$$

where the index j labels the spectral bands in the model. The third method available is based on that used in the radiative transfer model Streamer (Key 1995), which employs Mie calculations with spherical ice particles to compute ice cloud extinction coefficients by

$$e_{ice}(v) = A_v \left(r_{ice}\right)^{B_v} + C_v \tag{5}$$

where r_{ice} is the effective ice radius (in microns) and A_v, B_v and C_v are spectrally dependent parameters. As in the liquid parameterization based on Hu and Stamnes (1993) (which forms the inspiration for the Streamer ice cloud parameterization), this equation, with the expression for the single-scattering albedo, can be used to determine an appropriate absorption coefficient for any effective radius for each of RRTM's spectral bands.

Once the cloud optical depth is known, radiative transfer for each g-point in every band can be performed for the cloudy layer, with absorption due to clouds and absorption due to gases being considered equivalently. That is, the outgoing radiance is given by

$$\begin{aligned} R = {} & R_0\left[f_{cld}\left(1-A_{tot}\right) + \left(1-f_{cld}\right)\left(1-A_{gas}\right)\right] \\ & + \left[f_{cld}\left(B_{tot}A_{tot}\right) + \left(1-f_{cld}\right)B_{gas}A_{gas}\right] \end{aligned} \tag{6}$$

where R_0 is the incoming radiance, A_{gas} is the gaseous absorptance, B_{gas} is the effective Planck function for gas emission only, B_{tot} is the effective Planck function for all emission, and A_{tot} is given by

$$A_{tot} = A_{cld} + A_{gas} - A_{cld}\, A_{gas} \tag{7}$$

where A_{cld} is the absorptance of the cloud.

Shortwave Method

As in the longwave, the boundaries of the spectral bands in RRTM for the shortwave region were chosen as a consequence of the absorption band structure of the absorbing species in this region. A list of RRTM's bands, both longwave and shortwave, and the species treated in each band are presented in Table 1.

Table 1. RRTM bands.

	Species treated in RRTM	
Wavenumber range (cm^{-1})	**Lower atmosphere**	**Middle/upper atmosphere**
10 - 250	H_2O	H_2O
250 - 500	H_2O	H_2O
500 - 630	H_2O, CO_2	H_2O, CO_2
630 - 700	H_2O, CO_2	CO_2, O_3
700 - 820	H_2O, CO_2	CO_2, O_3
820 - 980	$H_2O^{*,**}$	--*
980 - 1080	H_2O, O_3^{**}	O_3
1080 - 1180	$H_2O^{*,**}$	O_3
1180 - 1390	H_2O, CH_4	CH_4
1390 - 1480	H_2O	H_2O
1480 - 1800	H_2O	H_2O
1800 - 2080	H_2O, CO_2	--
2080 - 2250	H_2O, N_2O	--
2250 - 2380	CO_2	CO_2
2380 - 2600	N_2O, CO_2	--
2600 - 3250	H_2O, CH_4	CH_4
3250 - 4000	H_2O, CO_2	H_2O, CO_2
4000 - 4650	H_2O, CH_4	CH_4
4650 - 5150	H_2O, CO_2	CO_2
5150 - 6150	H_2O^{****}	H_2O^{****}
6150 - 7700	H_2O, CO_2	H_2O, CO_2
7700 - 8050	H_2O, O_2	O_2
8050 - 12850	H_2O	--
12850 - 16000	H_2O, O_2^{***}	O_2^{***}
16000 - 22650	H_2O^{***}	--***
22650 - 29000	--	--
29000 - 38000	O_3	O_3
38000 - 50000	O_2, O_3	O_2, O_3
minor species implemented: *halocarbons; **CO_2; ***CO_3; ****CH_4.		

In each band, all spectrally dependent physical quantities that are used have been implemented in a manner that takes into account their respective spectral correlations with the absorption spectrum of the band, ensuring that appropriate values of these quantities are used for each sub-interval in the band. In particular, this is done for the solar source function used in RRTM (Kurucz 1994). For each band, the highest layer in the midlatitude summer (MLS) atmosphere above which substantial attenuation (~10%) of the solar beam has occurred is determined. The mapping from spectral space to 'g-space' that defines the k-distribution for this layer is then applied to the solar source function, and an irradiance value is obtained for each sub-interval in the band. These top-of-the-atmosphere irradiance values are used in RRTM as the starting point for the solar radiative transfer method.

The importance of following this approach can be seen by comparing the results obtained using this method with a modified version of RRTM in which an average value of each band's solar irradiance is used for all sub-intervals in the band. For the MLS atmosphere and a zenith angle of 0°, the standard version of RRTM computes a direct surface flux of 1122.60 W m^{-2}, with 244.10 W m^{-2} being absorbed in the atmosphere. For the modified version of the model, this absorption increased by 11.10 W m^{-2}, with a computed surface flux of 1111.50 W m^{-2}. This substantial difference, plus a similarly large difference resulting from a comparable experiment involving the implementation of Rayleigh extinction in RRTM, illustrates the importance of respecting the spectral nature of key physical quantities when developing a rapid radiative transfer model.

Shortwave Validations

Detailed comparisons of RRTM's calculations of direct solar fluxes and cooling rates with similar calculations using a line-by-line method have been performed for a range of atmospheric profiles. Presented in Table 2 are the band-by-band surface fluxes (no Rayleigh extinction) calculated by RRTM and LBLRTM for the MLS atmosphere with the sun at nadir. The agreement is good between the models for all bands, with no difference greater than 0.7 W m^{-2}. In addition, both models have performed this calculation with no water vapor continuum, allowing the determination of the effect in the shortwave region of this critical longwave absorber. Figure 1 shows the direct solar flux absorbed by the water vapor continuum (CKD_2.1 model [Clough et al. 1989]) as calculated by both models, and shows good agreement for all spectral bands. This calculation has repeated for a range of zenith angles, with the results presented in Figure 2. Using the value at 60° as a day-time mean, the diurnally-averaged solar flux absorbed by the water vapor continuum is approximately 2.5 W m^{-2}.

Table 2. Surface fluxes calculated by RRTM and LBLRTM for the MLS atmosphere with sun at nadir.

Wavenumber range (cm^{-1})	TOA	RRTM	LBLRTM	RRTM-LBLRTM
10 - 2600	13.2	3.99	3.77	0.22
2600 - 3250	12.1	6.33	5.85	0.48
3250 - 4000	20.4	0.33	0.46	-0.13
4000 - 4650	23.7	17.87	17.73	0.14
4650 - 5150	22.4	14.42	14.15	0.27
5150 - 6150	55.6	29.08	29.68	-0.60
6150 - 7700	102.9	47.33	47.62	-0.29
7700 - 8050	24.3	23.52	23.48	0.04
8050 - 12850	345.7	281.73	282.42	-0.69
12850 - 16000	218.2	203.26	203.02	0.24
16000 - 22650	347.2	338.58	338.43	0.15
226500 - 29000	129.5	129.46	129.46	0.00
29000 - 38000	48.4	26.70	27.39	-0.69
38000 - 50000	3.1	0.00	0.01	-0.01
10 - 50000	1366.7	1122.60	1123.47	-0.87

Future Work

Development of RRTM will be directed in two major areas in the near future. First, validated two- and/or four-stream multiple scattering capabilities will be added to the model, allowing its use as a complete radiative transfer package within a climate model. In addition, research devoted to the determination of the effect of replacing the longwave radiative transfer module in a general circulation model with RRTM (Iacono et al. 1997) will be greatly expanded.

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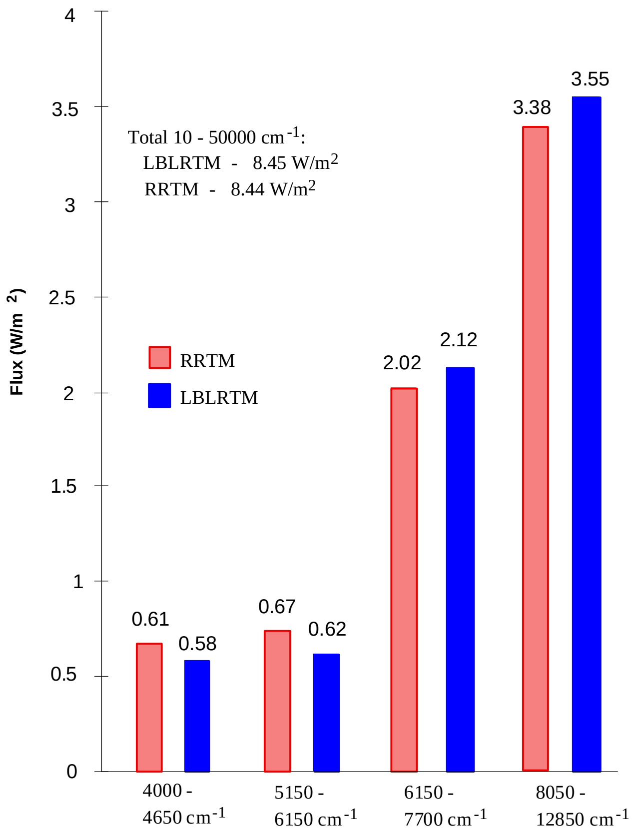

Figure 1. Direct solar flux absorbed by water vapor continuum for MLS atmosphere with sun at nadir as calculated by RRTM and LBLRTM for selected spectral regions.

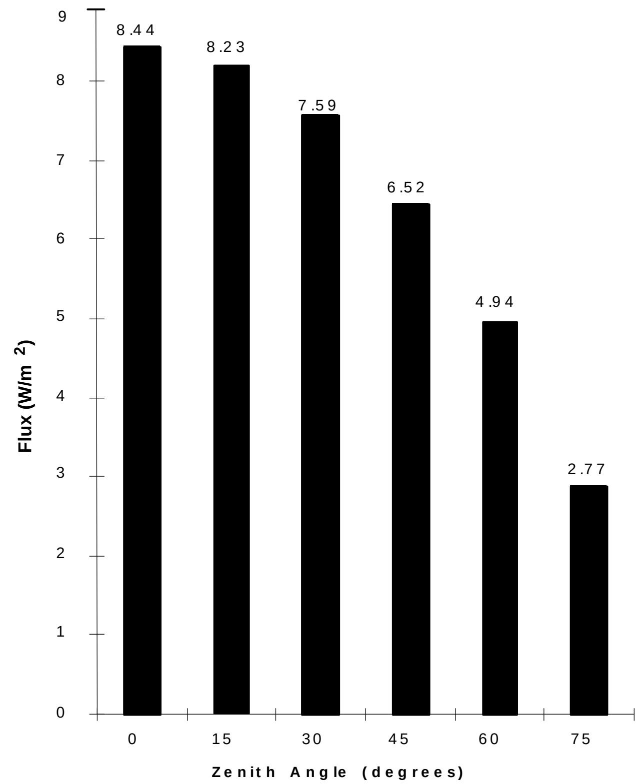

Figure 2. Direct solar flux absorbed by water vapor continuum for a range of solar zenith angles for MLS atmosphere as calculated by RRTM.

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