On the Extension of Rapid Radiative Transfer Model to the Shortwave Region

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Introduction

In this work we describe the second phase in the development of the rapid radiative transfer model (RRTM) (Mlawer et al. 1996), a rapid and accurate radiative transfer 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. Results from this method have been verified by validations performed using the line-by-line radiative transfer model (LBLRTM) (Clough et al. 1992; Clough and Iacono 1995) for atmospheric profiles spanning a wide range of conditions. The accuracy of LBLRTM, which provides the absorption coefficients for the k-distributions used by RRTM, has been established, in turn, by extensive high-resolution validations with measurements, particularly those performed in the long-wave region as part of the Atmospheric Radiation Measurement (ARM) program (Brown et al. 1996). These validations provide a traceable link from RRTM to observations done at high spectral resolution.

The present developmental phase of RRTM extends its long-wave approach to the shortwave region, allowing the calculation of direct solar fluxes and cooling rates for the spectral range 2,600-50,000 cm^{-1}. The optical depths needed in this range can be evaluated at arbitrary pressure and temperature for any combination of water vapor, carbon dioxide, ozone, and oxygen abundances. The results of these calculations by RRTM have been compared to line-by-line calculations and show substantial agreement.

Longwave Method and Validation

In the longwave calculations of RRTM, absorption due to water vapor, carbon dioxide, ozone, nitrous oxide, methane, CFC-11, CFC-12, CFC-22, and CCl_4 is considered. Accurate calculation of the radiative effect of these gases necessitates dividing the longwave region into a series of spectral bands, each of which contains strong absorption bands due to a limited number of gases. The effect of the key absorbers in each spectral band is treated with high accuracy, with a more approximate method employed for the absorption due to minor absorbing species in the band. Each spectral band in RRTM is divided into 16 intervals of unequal size, including 7 intervals placed in the section of the k-distribution corresponding to the highest 2% of absorption coefficient values. This variability in the size of RRTM's sub-intervals is needed to obtain suitable accuracy in the calculation of the cooling rate in the middle atmosphere, while preserving computational efficiency for all cases.

The method utilized in RRTM for handling a spectral band with overlapping absorbing species involves the use of a parameter, termed the binary species parameter, that reflects the relative radiative importance of the band's two greatest absorbing species. In this method, reference absorption coefficients in the band are computed using LBLRTM and stored for a range of values of this parameter (adding this parameter to the matrix of pressure and temperature values for which absorption coefficients are stored for all bands), allowing linear interpolation to accurately and efficiently determine absorption coefficients for the atmosphere in question.

In RRTM, all spectrally dependent physical quantities are utilized in each spectral band in a manner consistent with their respective correlations with the spectral distribution of the band's absorption coefficients. This includes the Planck function, the contribution of minor species to absorption in the band, and the effect of the water vapor self-continuum.

Validations of RRTM using LBLRTM have been performed for many atmospheric profiles, including the midlatitude summer, tropical, midlatitude winter, and subarctic winter. Based upon these validations, the longwave accuracy of RRTM for any atmosphere is as follows: 0.6 W m^{-2} (relative to LBLRTM) for net flux in each band at all altitudes, with a total (10-3000 cm^{-1}) error of less than 1.0 W m^{-2} at any altitude; 0.07 K d^{-1} for total cooling rate error in the troposphere and lower stratosphere and 0.75 K d^{-1} in the upper atmosphere.

The longwave validation for the midlatitude summer atmosphere is shown in Figure 1. Figure 1 presents the differences between the calculations of RRTM and LBLRTM for up, down, and net flux (defined as up flux minus down flux) as a logarithmic function of pressure. For reference, the results of the calculation of these respective quantities by LBLRTM are provided in Figure 1. The residuals for each of these quantities do not exceed 0.65 W m^{-2} at any altitude and represent only a small percentage of their respective value. Figure 1 indicates that the error in the cooling rate calculation is different in magnitude in the lower and upper altitude regimes. In the lower region, the maximum error is less than 0.06 K d^{-1}. The small magnitude of the error is maintained for a large portion of the stratosphere, but increases to greater than 0.5 K d^{-1} near 1 mb. This larger error is primarily caused by the calculation by RRTM in the upper atmosphere of overly large downward fluxes due to carbon dioxide in the 630-700 cm^{-1} spectral range.

Comparisons have also been made between the flux and cooling rate calculations of RRTM and LBLRTM for each spectral band in RRTM. These comparisons show that RRTM achieves accuracy on a band-by-band basis, assuring that the agreement between the models in Figure 1b is not due to cancellation of large errors of opposite signs from the individual bands, although some cancellation does occur.

Other longwave comparisons have been performed using LBLRTM to gauge RRTM's sensitivity to changes in the abundance of specific species, including the halocarbons and carbon dioxide. The radiative forcing due to doubling the concentration of carbon dioxide is attained with an accuracy of 0.24 W m^{-2}, an error of less than 5%.

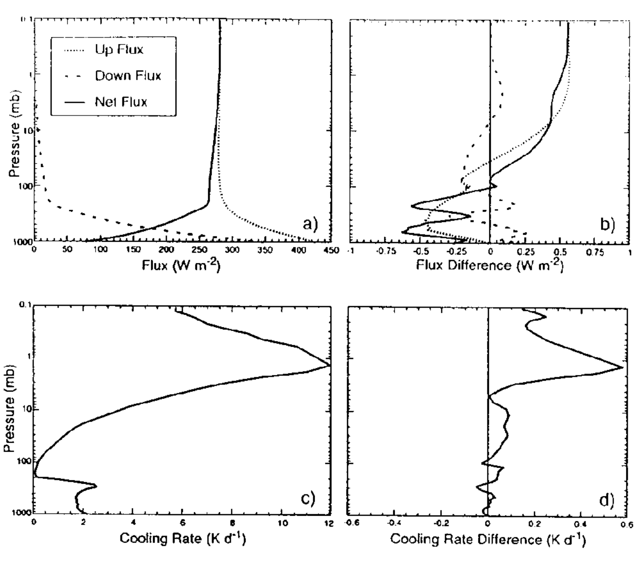

Figure 1. For the MLS atmosphere: (a) longwave fluxes calculated by LBLRTM (b) differences in fluxes between RRTM and LBLRTM (c) cooling rates calculated by LBLRTM (d) differences in cooling rates between RRTM and LBLRTM.

Shortwave Bands

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. Instrumental in the choice of the boundaries of the solar bands has been the development of a heuristic factor which provides a measure of the capacity of each gas in a layer to absorb solar radiation at a given wavenumber. This factor, called the Layer Solar Radiance Absorption Factor, is defined as

$$F\nu = R\nu sp \ \tau\nu \qquad (1)$$

where $R\nu sp$ is the solar radiance at wavenumber ν incident at the top of the atmosphere at zenith and $\tau\nu$ is the optical depth. Although it has limitations, this factor provides a quick and effective tool to compare the ability of gases at different wavenumbers to attenuate solar radiation. As an example of its utility, Figure 2 shows values of this factor for gases in the spectral domain 10000-25000 cm^{-1} for a typical surface layer in the MLS atmosphere. The values of F displayed in this figure were computed using solar radiances and optical depths that were averaged in 10 cm^{-1} intervals. Also indicated in Figure 2 are the boundaries of the spectral bands chosen with the aid of this method.

The choice of spectral bands in the solar region has been facilitated by the use of direct solar heating rates for a model atmosphere computed using MODTRAN2 (Bernstein et al. 1996) as a function of wavenumber and pressure.

Shortwave Validations

In order to calculate the direct solar fluxes throughout the atmosphere at a given zenith angle, RRTM requires a value of the downwelling solar flux at the top of the atmosphere for each sub-interval in each band. For the initial version of the solar radiative transfer code, this was accomplished by mapping the Planck function at T=5780K in each band (integrated over the solar disk to obtain irradiances) using the transformation that generates, for a chosen reference layer, a k-distribution from the spectrally-dependent absorption coefficients in the band. These mapped Planck function values are then summed in each sub-interval. In future

Table 1. RRTM Bands.

Wavenumber Range (cm^{-1})	Species Treated in RRTM: Lower Atmosphere	Species Treated in RRTM: 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 (a)	CO_2, O_3 (a)
820 - 980	H_2O (a), (b)	-- (a)
980 - 1080	H_2O, O_3 (b)	O_3
1080 - 1180	H_2O (a), (b)	O_3 (b)
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	CO_2, N_2O	--
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	CO_2
7700 - 8050	H_2O, CO_2	O_2
8050 - 12850	H_2O	--
12850 - 16000	H_2O, O_2 (c)	O_2 (c)
16000 - 22650	H_2O (c)	-- (c)
22650 - 29000	--	--
29000 - 38000	O_3	O_3
38000 - 50000	O_2, O_3	O_2, O_3

(a) Halocarbons implemented as minor species.
(b) CO_2 implemented as minor species.
(c) O_3 implemented as minor species.

versions of the model, a more sophisticated solar source function (Kurucz 1994) will be used.

The RRTM calculations of direct solar fluxes and cooling rates were compared to those of a simple line-by-line method that used optical depths supplied by LBLRTM and the T=5780K Planck function as a solar source function. The two models were compared for a variety of atmospheric profiles and showed substantial agreement. Figure 3 shows the

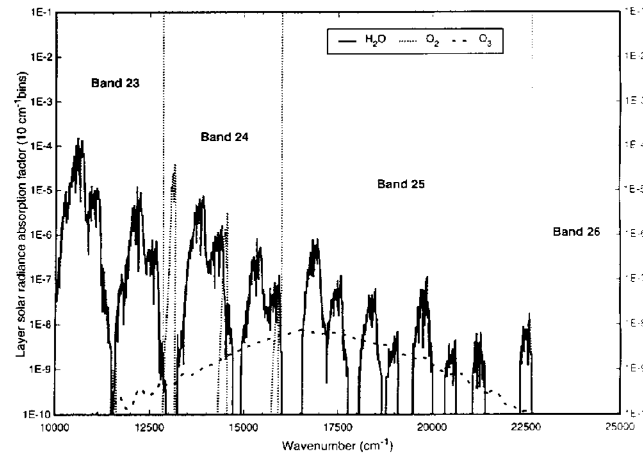

Figure 2. The Layer Solar Radiance Absorption Factor (Eq. 1) for absorbing gases in the spectral range 10,000-25,000 cm for a surface layer (0-1.1 km) in the MLS atmosphere.

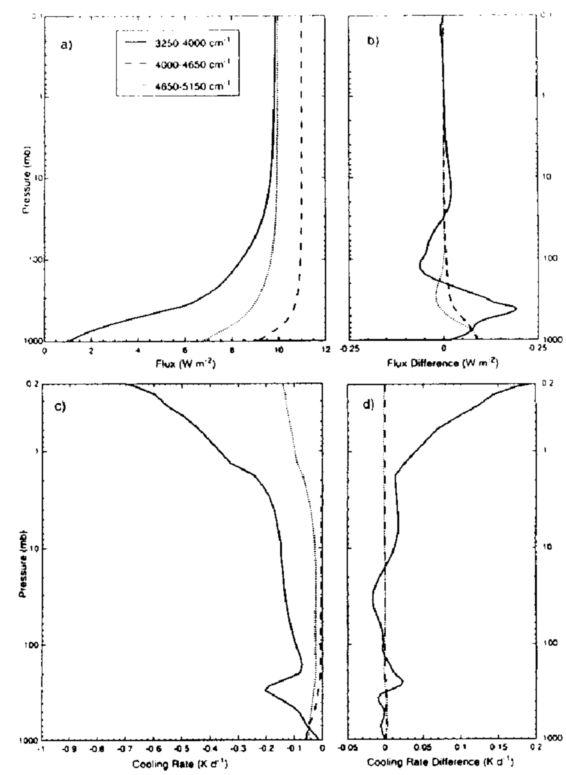

Figure 3. For the MLS atmosphere and zenith angle of 60^o: (a) direct solar fluxes from line-by-line calculations (b) differences in fluxes between RRTM and line-by-line (c) direct solar cooling rates from line-by-line calculations (d) differences in cooling rates between RRTM and line-by-line.

results for this comparison for three bands in RRTM for the midlatitude summer atmosphere and a zenith angle of 60º. The differences in the calculation of direct solar flux (Figure 3b) are less than 0.25 W m^{-2} at all altitudes in each band, and the cooling rate differences (Figure 3d) do not exceed 0.03 K d^{-1} in the troposphere and lower stratosphere. Some of these differences may be attributed to the current lack of consideration in RRTM of absorption in these bands due to N_2O.

Future Work

To allow the immediate applicability of this work to climate study, the k-distributions developed for RRTM will be incorporated into the ARM collaborative model 3ARM (Bergstrom et al. 1996). This will be followed by the implementation in RRTM of a validated two- and four-stream multiple scattering capability.

Acknowledgments

The authors would like to thank Pat Brown, Mike Iacono, and Ned Snell for their assistance and Gail Anderson providing the MODTRAN2 heating rate calculations. This research was supported by the U.S. Department of Energy (DE-FG02-90ER61064).

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