RRTM: A Rapid Radiative Transfer Model

E. J. Mlawer, S. J. Taubman,[(a)] and S. A. Clough
Atmospheric and Environmental Research, Inc.
Cambridge, Massachusetts

Introduction

A rapid radiative transfer model (RRTM) for the calculation of longwave clear-sky fluxes and cooling rates has been developed. The model, which uses the correlated-k method, is both accurate and computationally fast. The foundation for RRTM is the line-by-line radiative transfer model (LBLRTM) from which the relevant k-distributions are obtained. LBLRTM, which has been extensively validated against spectral observations (e.g., the high-resolution sounder and the Atmospheric Emitted Radiance Interferometer [Brown et al. 1995]), is used to validate the flux and cooling rate results from RRTM. Validations of RRTM's results have been performed for the tropical, midlatitude summer, and midlatitude winter atmospheres, as well as for the four Intercomparison of Radiation Codes in Climate Models (ICRCCM) (Ellingson and Fouquart 1991) cases from the Spectral Radiance Experiment (SPECTRE). Details of some of these validations are presented below. RRTM has the identical atmospheric input module as LBLRTM, facilitating intercomparisons with LBLRTM and application of the model at the Atmospheric Radiation Measurement Cloud and Radiation Testbed sites.

Optical Depths

RRTM divides the longwave spectral region into 16 bands chosen for their homogeneity of contributing species and radiative transfer properties. A list of these bands and their respective key species is presented in Table 1. The selection of the spectral regions is facilitated by consideration of the Plates of spectral cooling rate as a function of log pressure provided by Clough and Iacono (1995).

In RRTM, all the optical depths in a given spectral band are represented by a small set of characteristic values that are used to perform the radiative transfer. The procedure that determines these characteristic values begins with the creation of a k-distribution, which involves assigning to each absorption coefficient k(v) a value g ($0 \le g \le 1$) that represents the fraction of the absorption coefficients in the band smaller than k(v). This procedure arranges the k-values in ascending order and defines a mapping $v \rightarrow g$ that provides an important perspective in the development of the model (West et al. 1990). The function k(g) is then divided into a small number of intervals, each having a limited range of k(g) values, and a representative value $k(g_i)$ is obtained for each interval. Since the equations used to calculate radiances have no explicit dependence on wavenumber, $k(g_i)$ can be used to estimate the radiance for the entire interval. The resulting radiances, weighted by the sizes of their respective intervals, can then be summed to yield the total radiance for the spectral band.

Table 1. RRTM Bands.

Wavenumber Range (cm^{-1})	**Key Species in RRTM**	
	1050-96 mb	**96-0.01 mb**
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	--
2600-3000	H_2O, CH_4	--

(a) Currently at Geophysical Fluid Dynamics Laboratory.

This method for calculating radiances for inhomogeneous atmospheres is referred to as the correlated-k method.

Each spectral band in the RRTM is broken into 16 intervals with half-gauss quadrature spacing modified such that 7 intervals lie between g = 0.98 and g = 1.0. This modified quadrature spacing is done to better represent the high values of k(g) associated with the centers of the spectral lines. For RRTM we have chosen to calculate each $k(g_i)$ by averaging the k(g) values in each interval so as to include the contribution from every k-value in the interval. The full set of k-values comes from LBLRTM, which uses the water vapor continuum model CKD_2.1 (Clough et al. 1989) and the 1992 HITRAN line parameter database (Rothman et al. 1992).

For an arbitrary atmosphere, $k(g_i)$ values are obtained by linear interpolating in log pressure and temperature stored values of $k(g_i)$. In bands with more than one key contributing species, an additional interpolation is performed in a parameter, η, that represents the relative (strength-weighted) abundance of the two most critical species, which greatly affects the mapping $v \rightarrow g$. This parameter, called the binary species parameter, is defined as

$$\eta \equiv \frac{S_1 W_1}{S_1 W_1 + S_2 W_2}, \qquad (1)$$

where S_i is the integrated line strength of species over the spectral band and W_i is the layer column amount of that species. For these overlap bands, values of $k(g_i)$ are stored for reference atmospheres with values of η equal to 0, 1/8, 2/8,...,1 for a given pressure and temperature in the lower atmosphere and for values of η equal to 0, 1/4, 1/2, 3/4, and 1 in the upper atmosphere. For certain bands the species considered most critical are changed with altitude regime (see Table 1). In all bands, reference $k(g_i)$ values are stored for 59 pressure levels from 1050 - 0.01 mb, with a fixed ratio of ~1.2 between successive pressure values. At each reference pressure level, $k(g_i)$ values are stored at 5 temperatures T_{ref}, $T_{ref} \pm 15K$, $T_{ref} \pm 30K$, where T_{ref} is obtained from the midlatitude summer temperature profile. The $k(g_i)$ values that are the result of this interpolation procedure include the spectral line contributions from the major species and the water vapor foreign continuum.

The contribution of the water vapor self-continuum to the optical depth is included by a separate procedure due to its quadratic dependence on water vapor abundance. First, the mapping $v \rightarrow g$ for all absorbers in each band is determined for two midlatitude summer atmospheric layers at 296 K and 260 K. The two mappings are then applied to the self-continuum absorption coefficients in the band at the respective temperatures. This procedure yields, at each temperature, a set of average self-continuum absorption coefficients $k_s(g_i)$, which are used to obtain the values of $k_s(g_i)$ at any temperature by appropriately interpolating. Finally, the contribution of the self-continuum to the optical depth is computed by multiplying $k_s(g_i)$ by a scaling factor that is quadratic in water vapor density.

Radiative Transfer Algorithm

RRTM performs a separate radiative transfer through the specified altitude range for each interval in each band. This, in effect, treats each interval, which "represents" a large number of frequencies in the band, in the same manner as a single spectral point is treated in a line-by-line model. As does LBLRTM, RRTM makes use of the "linear in τ" approximation for vertically inhomogeneous atmospheres and uses a Pade approximation to calculate an effective Planck function for each layer (applicable for any τ in the layer) by creating an appropriately weighted combination of the Planck function at the layer boundary temperature and the Planck function at the mean layer temperature (Clough et al. 1992). However, for a model using the correlated-k method, it is non-trivial to determine the appropriate (layer and level) Planck functions for any interval in a band since the Planck functions evaluated at all frequencies that are associated with that interval must be taken into account. Moreover, the mapping $v \rightarrow g$ can vary dramatically with atmospheric properties, especially the abundance of the band's key species, thereby limiting the accuracy of approximating the Planck function for the interval by the value of the Planck function at a single "dominant" frequency. This issue is addressed in RRTM by a two-part procedure. First, the integrated Planck energy for a band is a function only of temperature and is easily calculated and stored. The fraction of this energy that is due to the frequencies associated with an interval, defined by

$$f_g \equiv \frac{B_g W_g}{\frac{1}{\nu_2 - \nu_1} \int_{\nu_1}^{\nu_2} B_\nu(T) d\nu}, \qquad (2)$$

where B_g is the average Planck function of the frequencies in the interval, W_g is the weight for the interval, and ν_1 and ν_2 are the frequency boundaries of the band, depends primarily on the mapping $v \rightarrow g$, which, in turn, is mainly dependent on the abundance of the band's key species. Therefore, for bands with one key species, f_g is considered constant. For bands with two key species, f_g is treated as a function of η and is computed by linear interpolation from stored f_g values calculated for reference values of η. All calculations performed to generate reference f_g values

for a band are done at a pressure level appropriate for that band and use a midlatitude summer atmospheric profile. At execution time, RRTM computes the Planck function for an interval by multiplying the calculated f_g by the integrated Planck function for the band. The use of this procedure to calculate the Planck function assures that the total Planck energy is correct at every level in each band. The radiances calculated by the methods described above are then integrated (which is approximated by a first-moment Gaussian quadrature) over a hemisphere to yield fluxes.

Timing

Results of preliminary timing tests for RRTM indicate that computing the fluxes and cooling rates for a 51-layer atmosphere, which includes the performance of 256 (16 intervals x 16 bands) upward and downward radiative transfer calculations and, therefore, the computation of 256 optical depths per layer, takes 0.05 s on a SPARCserver 1000. This compares favorably to other rapid radiative transfer models. A further indication of the computational efficiency of the model is that these radiative transfer operations in RRTM take 1.8 times the amount of time needed to perform 51 x 16 x 16 exponentials. Further evaluation of RRTM's timing is in progress.

Validations

The results of flux and cooling rate calculations performed by RRTM have been compared to those done by the LBLRTM for the midlatitude summer, midlatitude winter, and tropical atmospheres. Figures 1-4 show the results of these validations for the midlatitude summer atmosphere for the spectral range 10–980 cm^{-1}. RRTM and LBLRTM upward flux calculations at all altitudes differ by no more than 0.25 W/m^2 (Figure 2). For downward fluxes, errors of a few percent for the entire spectral range are typical in the upper atmosphere, with an error at the tropopause of 0.4 W/m^2. The errors in downward flux in the lower atmosphere are smaller, including an error in surface downward flux of 0.1 W/m^2. The errors in the heating rate calculations (Figure 4) also are smaller near the surface, with typical errors in the 1000-100 mb range of less than 0.05 K/day. Errors in cooling rates between 1.0 and 0.1 mb can be as high as 0.5 K/day. Similar results to these have been found for the midlatitude winter and tropical atmospheres. In addition, very satisfactory

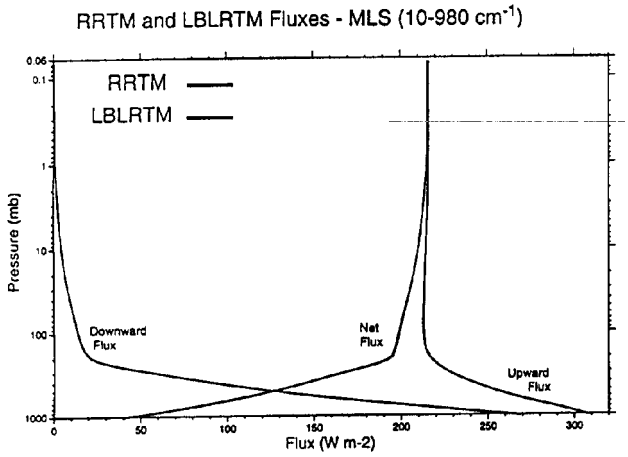

Figure 1. Fluxes as a function of log pressure from the LBLRTM and from the RRTM.

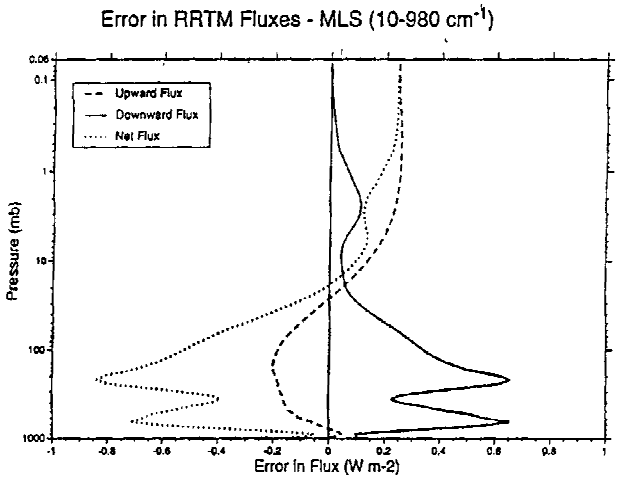

Figure 2. Difference between RRTM and LBLRTM fluxes as a function of log pressure.

results are obtained relative to both LBLRTM and observations for the calculation of downward surface radiance for the four SPECTRE atmospheres used in ICRCCM.

Summary

RRTM currently provides an accurate and rapid method for computing longwave fluxes and cooling rates for an arbitrary clear atmosphere. RRTM, due to its use of linear interpolation to determine all necessary physical

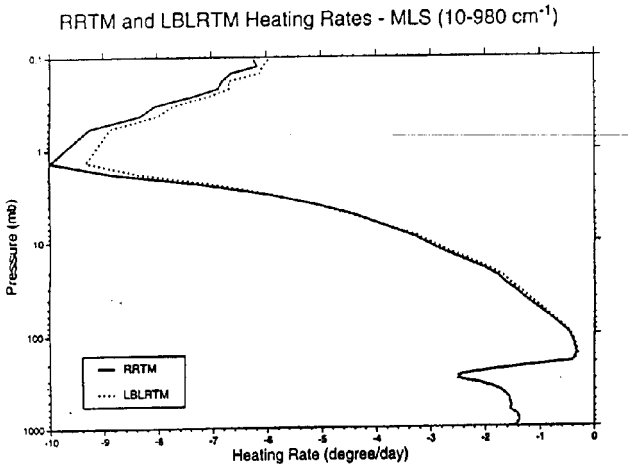

Figure 3. Heating rates as a function of log pressure from the LBLRTM and from the RRTM.

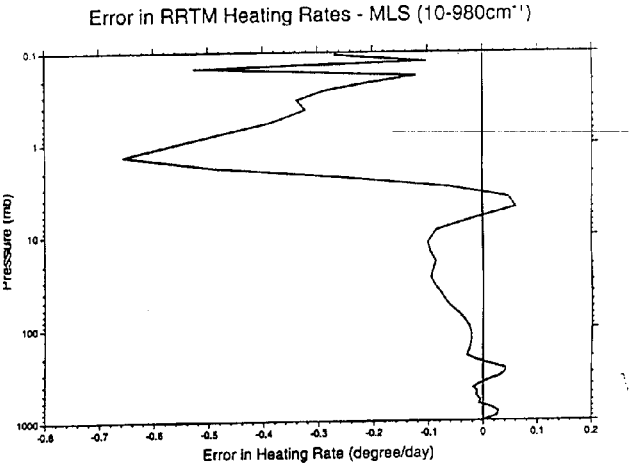

Figure 4. Difference between RRTM and LBLRTM heating rates as a function of log pressure.

quantities, does not suffer from discreteness problems, enabling the model to accommodate microlayering.

The next phase in the development of RRTM will involve the extension of the algorithm to include the shortwave region of the spectrum and will allow the calculation of fluxes and cooling rates for both clear and cloudy skies.

Acknowledgments

The authors would like to thank Luke Chen for providing the code used to create the k-distributions. The authors also wish to acknowledge the contributions of Robert Bergstrom, Patrick Brown, Ronald Farren, Richard Goody, and Michael Iacono. This research was supported by the Department of Energy (DE-FG02-9OER61064).

References

Brown, P. D., S. A. Clough, N. E. Miller, T. R. Shippert, D. D. Turner, R. O. Knuteson, H. E. Revercomb, and W. L. Smith. 1995. Initial analyses of surface spectral radiance between instrument observations and line by line calculations. In *Proceedings of the Fifth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, San Diego, California, (this volume).

Clough, S. A., F. X. Kneizys, and R. W. Davies. 1989. Line shape and the water vapor continuum, *Atmos. Res.*, **23**, 229-241.

Clough, S. A., M. J. Iacono, and J.-L. Moncet. 1992. Line-by-line calculations of atmospheric fluxes and cooling rates: Application to water vapor, *J. Geophys. Res.*, **97**, 15761-15785.

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.*, in press.

Ellingson, R. G., and Y. Fouquart. 1991. The intercomparison of radiation codes in climate models: An overview, *J. Geophys. Res.*, **96**, 8925-8927.

Rothman, L. S., R. R. Gamache, R. H. Tipping, C. P. Rinsland, M.A.H. Smith, D. C. Benner, V. Malathy Devi, J.-M. Flaud, C. Camy-Peret, A. Perrin, A. Goldman, S. T. Massie, L. R. Brown, and R. A. Toth. 1992. HITRAN molecular database: Edition '92, *J. Quant Spectrosc. Radiat. Transfer*, **48**, 469-507.

Toon, O. B., C. P. McKay, T. P. Ackerman, and K. Santhanam. 1989. Rapid calculation of radiative heating rates and photodissocation rates in inhomogeneous multiple scattering atmospheres, *J. Geophys. Res.*, **94**, 16287-16301.

West, R., D. Crisp, and L. Chen. 1990. Mapping transformations for broadband atmospheric radiation calculations, *J. Quant. Spectrosc. Radiat. Transfer* **43**, 191-199.